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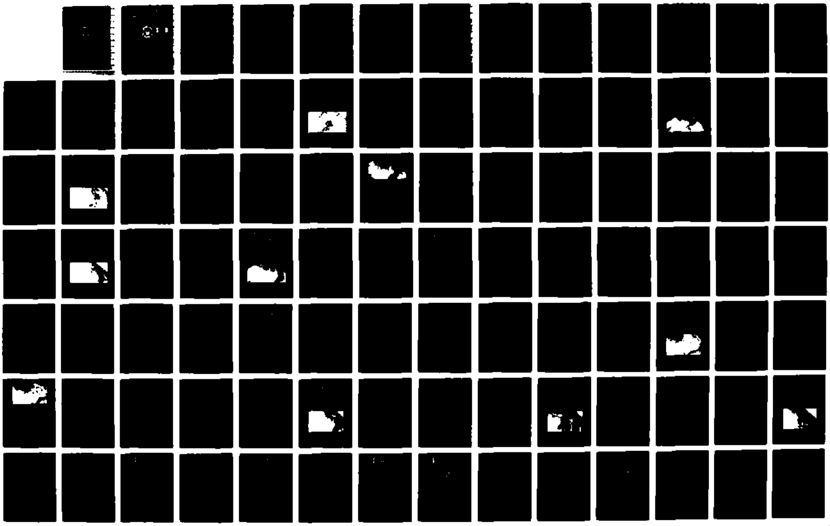

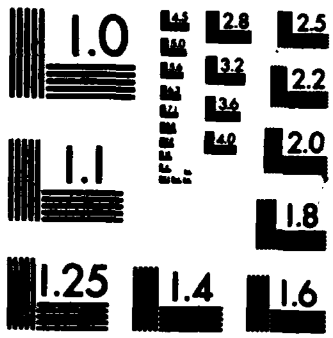

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THESIS

A SYNOPTIC INVESTIGATION OF
MARITIME CYCLOGENESIS DURING GALE

by

William E. Pertle

March 1987

Thesis Advisor Carlyle H. Wash

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A synoptic diagnosis of two intensive observation periods (IOP 1 and 9) of the Genesis of Atlantic Lows Experiment (GALE) is conducted. Operationally available data and some preliminary GALE data were used to describe key synoptic and subsynoptic features that are important to the coastal and ocean cyclogenesis, and explain the evolution of these features. Adequacy of the operational and GALE enhanced data sets to explore these features is addressed. A verification of the Navy Operational Regional Analysis and Prediction System (NORAPS) forecasts of these systems is conducted. In both cases mesoscale structure was important in understanding the cyclogenesis event. Cyclogenesis of both IOP 1 and 9 represent more complex interactions and processes than the simplified cyclogenesis suggested by the quasi-geostrophic theory.

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A Synoptic Investigation of Maritime Cyclogenesis during GALE

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND OCEANOGRAPHY

from the

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ABSTRACT

A synoptic diagnosis of two intensive observation periods (IOP 1 and 9) of the Genesis of Atlantic Lows Experiment (GALE) is conducted. Operationally available data and some preliminary GALE data were used to describe key synoptic and subsynoptic features that are important to the coastal and ocean cyclogenesis, and explain the evolution of these features. Adequacy of the operational and GALE enhanced data sets to explore these features is addressed. A verification of the Navy Operational Regional Analysis and Prediction System (NORAPS) forecasts of these systems is conducted. In both cases mesoscale structure was important in understanding the cyclogenesis event. Cyclogenesis of both IOP 1 and 9 represent more complex interactions and processes than the simplified cyclogenesis suggested by the quasi-geostrophic theory. Keywords: Weather forecasting; → (to p 1

TABLE OF CONTENTS

LIST OF FIGURES

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I. INTRODUCTION

Rapidly developing extratropical maritime cyclones pose an extreme hazard to naval operations, commercial shipping, oil platforms and coastal areas. According to Sanders and Gyakum (1980) and Roebber (1984), explosively deepening cyclones occur primarily in the cool season. Sanders and Gyakum (1980) define an explosively deepening cyclone as one characterized by a central pressure fall equivalent to one mb h^{-1} for 24 h at 60°N. Sanders and Gyakum (1980) indicate that this explosive deepening frequently occurs within an intense low-level baroclinic zone in the vicinity of a strong sea-surface temperature gradient The regions of maximum frequency of occurrence are in the western North Pacific and Atlantic Oceans.

Accurate forecasting of explosive maritime cyclogenesis is an important problem. Early warning is essential to preclude loss of life and to minimize damage due to the extreme weather conditions that accompany these cyclones. According to Sanders and Gyakum (1980), explosive cyclogenesis is generally poorly forecast by existing numerical models. The major sources of error in numerical models include data gaps, poor initialization, truncation errors and inaccurate model physics (Haltiner and Williams, 1980). Limited data availability over ocean areas is a significant source of model error. Because of the smaller spatial scales of rapidly developing oceanic systems, they are often not well resolved by available data. Our limited understanding of the dominant physical processes in the formation and explosive deepening of maritime cyclones further limits our modeling capability. This limitation indicates the need for further research into the physical processes of oceanic cyclogenesis.

In the recent past, there has been a dramatic increase in the ability to observe and model subsynoptic scale atmospheric processes. This progress emphasizes the importance of mesoscale processes in the formation and evolution of weather systems. In response to the need for improved understanding of mesoscale processes, the Genesis of Atlantic Lows Experiment (GALE) was conducted. GALE, a multi-agency, multi-university experiment, was the first large cooperative mesoscale experiment devoted to winter cyclones. The GALE objectives were to study the contribution of mesoscale and air-sea interaction processes to cyclogenesis over the east coast of the United States.

The GALE observational network was centered over the eastern Carolinas. The field experiment extended from 15 January through 15 March 1986. Explosive maritime cyclogenesis is commonly observed seaward of the Carolinas during this period. During the Intense Observation Periods (IOP's), special observations extended from the Rocky Mountains to several hundred miles off the east coast of the United States.

The GALE project provides an excellent opportunity to investigate the effects of improved temporal and spatial data resolution on numerical predictions of explosive maritime cyclogenesis. The addition of more frequent data over land and enhanced ocean data should improve resolution of coastal and maritime cyclogenesis. Careful synoptic diagnosis should identify the important physical processes to be investigated in more detail. An increased understanding of these key mesoscale processes should lead to improved model physical parameterizations and better forecasts.

This thesis constitutes a portion of a broadly-based Naval Postgraduate School research effort to better understand and predict explosive maritime cyclogenesis by employing a combined synoptic diagnosis and numerical modelling approach. Better understanding of the physical mechanisms and air-sea interactions will be the basis for more accurate numerical modelling schemes for ocean regions. In this thesis, two IOP's (IOP 1 and 9) with significant oceanic cyclogenesis are investigated. This initial GALE study is primarily synoptic in character, and is directed toward the study of the important synoptic and subsynoptic features in these IOP's. The adequacy of the operational and GALE enhanced data sets to explore these features will be addressed.

The overall thesis goal is to use the operationally available data and some of the preliminary GALE data to describe key synoptic and subsynoptic features that are important to the coastal and ocean cyclogenesis, explain the evolution of these features and verify the Navy Operational Regional Analysis and Prediction System (NORAPS) forecasts of these systems. The available GALE data will then be used to explore these key features further and focus future research work.

Specific thesis objectives are:

1. Present a detailed discussion of the key synoptic and subsynoptic features of IOP 1 and 9;
2. Conduct a verification of the NORAPS numerical prognoses for these IOP's;
3. Discuss the special data set coverage for each IOP with respect to key features above.

II. SYNOPTIC DISCUSSION OF IOP 1

Chapters two and three explore the synoptic conditions associated with two Intense Observation Periods (IOP 1 and 9) of the GALE project. IOP 1 extended from 0000 GMT 18 until 2100 GMT 20 January 1986, and IOP 9 from 1200 GMT 24 until 1200 GMT 26 February 1986. The synoptic evaluation initially will focus on the surface, 500 mb and upper-level (either 250 or 300 mb) features as represented by the Fleet Numerical Oceanography Center (FNOC) NORAPS objective analyses with surface frontal features as described by the subjective National Meteorological Center (NMC) final surface analyses, and GOES imagery. Verification of selected NORAPS prognoses then will be presented.

The figures for the synoptic analysis consist of six basic meteorological fields arranged as three pairs of fields for each synoptic period, complemented by associated satellite imagery. The pairs of fields consist of the sea-level pressure analysis and fronts with the 1000-500 mb thickness, the 500 mb geopotential heights with absolute vorticity and the 250 or 300 mb geopotential heights with isotachs. Synoptic and model figures contain continental boundaries, latitude lines and longitudinal meridians with 10° spacing. The analysis sector is centered on 40°N, 80°W.

The intent of the following sections is to trace the cyclogenesis within the IOP's through a discussion of the major associated synoptic features. More detailed analyses, NORAPS validations, and descriptions of GALE data opportunities then follow.

The GALE rawinsonde network was divided into inner, outer and regional areas. The inner area encompassed coastal Virginia, North and South Carolina, including eight Cross-chain LORAN-C Atmospheric Sounding Systems (CLASS) sites, two National Weather Service automated radiotheodolite (ART) sites, one ground meteorological direction-finder (GMD) radiosonde site and two other radiosonde sites. The regional area encompassed most of the southeastern U.S. with the exception of southern Florida and western portions of Kentucky, Tennessee and Alabama. The outer area extended as far west as the 100°W and as far east as 65°W (GALE, 1985).

At 1200 GMT 18 January 1986, all the CLASS sites and most inner, regional and outer sites began a three-hour launch schedule for this IOP (GALE, 1986). From 1500 GMT 19 until 0000 GMT 20 January the CLASS sites and Petersburg VA maintained

a 90-minute launch interval. The augmented schedule of 3-h rawinsonde launches terminated after 1200 GMT 20 January.

A. 1200 GMT 18 JANUARY 1986

The two mid-tropospheric troughs responsible for the IOP 1 cyclogenesis are analyzed over the middle of the United States early in IOP 1 at 1200 GMT 18 January 1986. The first trough over Louisiana (Fig. 2.1) has been slowly moving eastward across the southern United States for the past few days. This trough is marked by a strong absolute vorticity maximum over Louisiana with a weaker maximum to the east over Georgia. Flow through these maximums produce a general positive vorticity advection (PVA) area along the Gulf Coast east of New Orleans.

This trough has no surface signature. The ridging with an intense 1036 mb North Atlantic Ocean anticyclone extends to the Mississippi River Valley (Fig. 2.2). The 1000-500 mb thickness analysis reveals a weak baroclinic zone south of the ridge line. This baroclinicity is a remnant of an old cold front which moved across the southeastern United States over the past several days. The surface and 1000-500 mb thickness analyses indicate weak warm air advection at low levels over Florida and adjacent waters.

The first trough is less distinct in the upper troposphere than at 500 mb (Fig. 2.3). The 300 mb analysis indicates the upper trough is vertically aligned with the 500 mb trough over the Mississippi River Valley. The 300 mb and 250 mb analysis (not shown) indicate a zone of higher winds is present east of the trough with a maximum of 40 m s^{-1} east of Florida. This maximum indicates a confluent structure to the trough with a net export of vorticity.

GOES satellite imagery reveals a surprising amount of cloudiness with this system. The GOES visible sector from 1531 GMT (Fig. 2.4) indicates an elongated comma pattern with cyclonically curved cloud bands over Georgia and Alabama and a dense cloud band from the Bahamas southwestward to southern Mexico. The GOES infrared (IR) sector from 1201 GMT (not shown) indicates that most of the cloud tops over Florida are at the middle to high levels.

An investigation of the surface observations from 1200 GMT also indicates that clouds associated with this system are mainly middle and high with only limited precipitation activity. West Palm Beach, FL reported rainshowers while Miami, FL reported the end of rainshower activity. The remainder of Florida and the southeastern

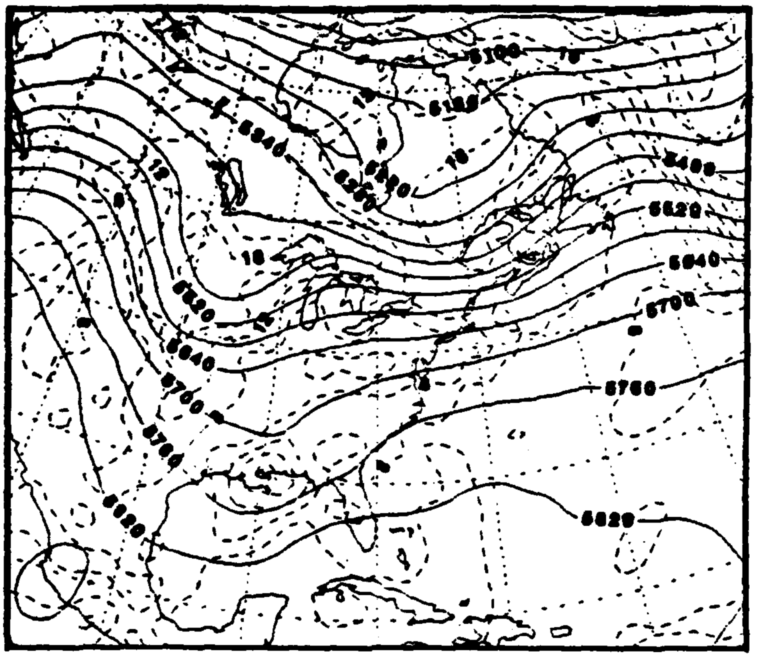

Figure 2.1 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) $10^{-5}s^{-1}$ valid 1200 GMT 18 January 1986.

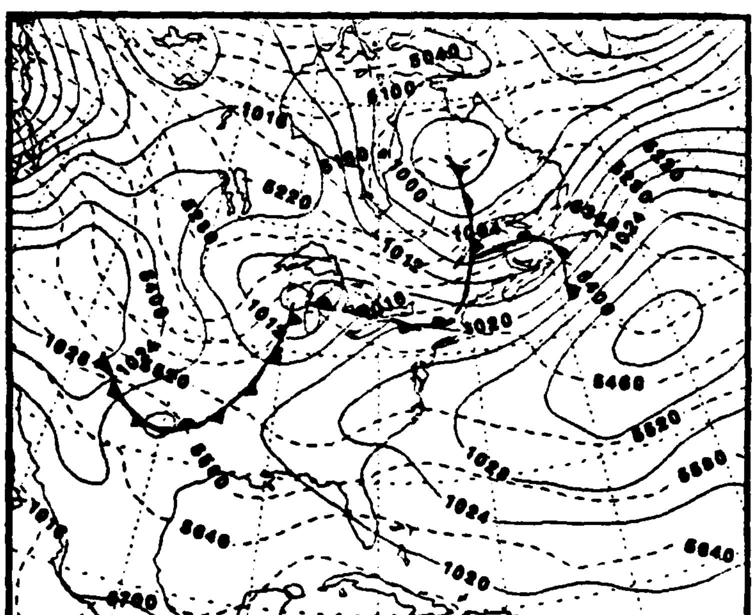

Figure 2.2 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 1200 GMT 18 January 1986.

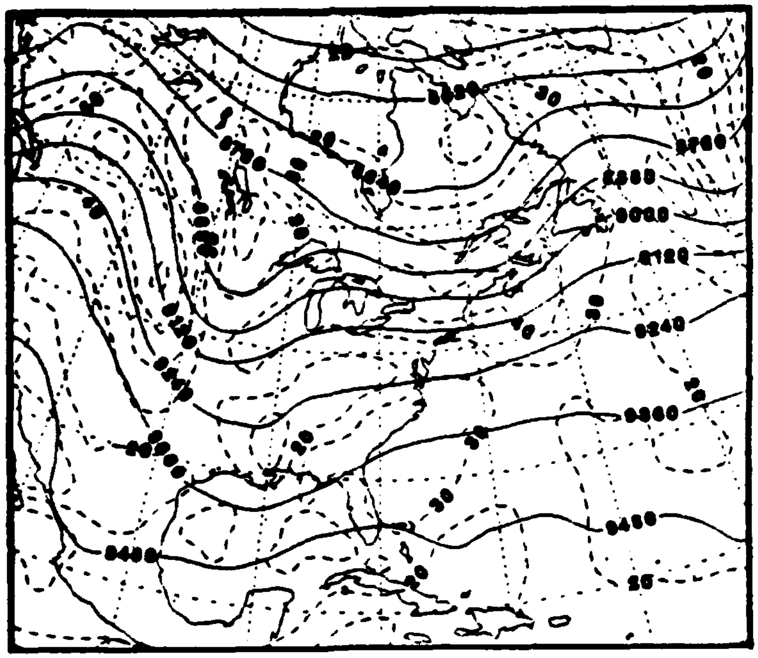

Figure 2.3 300 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 300 mb valid 1200 GMT 18 January 1986.

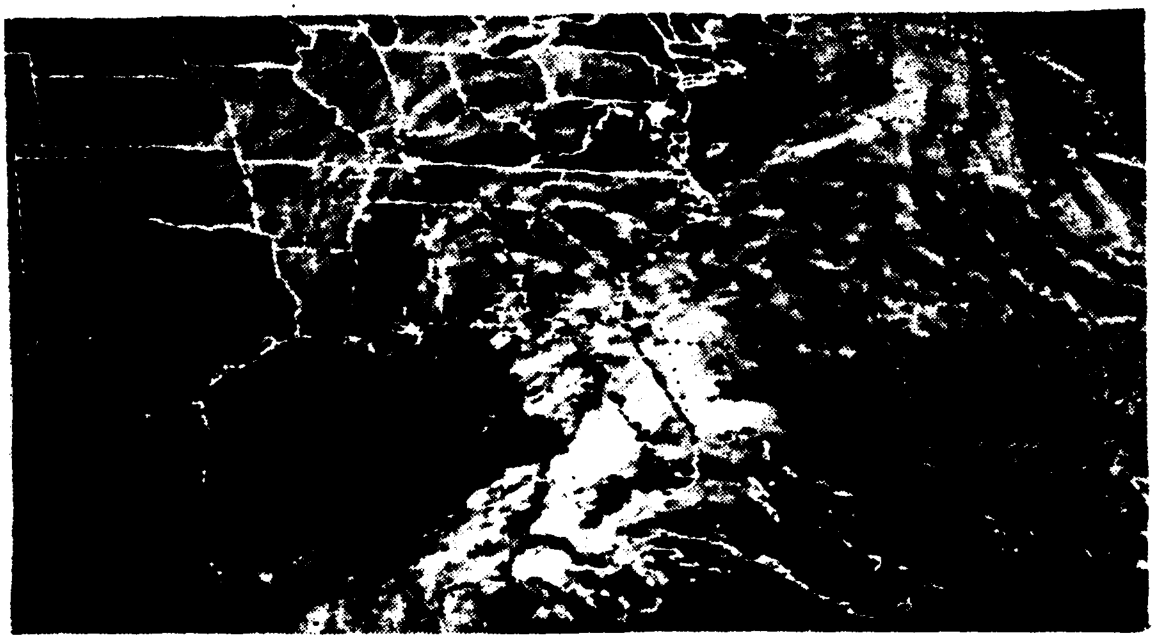

Figure 2.4 GOES visible satellite image valid 1531 GMT 18 January 1986.

United States reported shallow fog. Deep fog blanketed the reporting stations in Louisiana and along the Texas Gulf Coast. The widespread occurrence of fog indicates a strong influx of moisture in the southeasterly flow and a capping inversion over the southeastern United States.

Analysis of the Athens, GA rawinsonde (not shown) reveals a strong surface based inversion extending to 950 mb. This sounding is saturated to 975 mb and nearly saturated to the base of a second elevated inversion based at 780 mb. The Waycross GA rawinsonde (not shown) is quite similar to the Athens sounding, except that the second inversion is based at 675 mb over Waycross. The West Palm Beach rawinsonde differed significantly from both Athens and Waycross reports. There is no surface based inversion, and the sounding is conditionally unstable to an elevated inversion based at 650 mb. Significant moisture extends to 650 mb, with a much dryer layer above. These soundings indicate the rainshower activity was in an area of weak stability over southeastern Florida.

The second trough system of IOP 1 over the upper Midwest (Fig. 2.1) is moving rapidly southeastward, after having traversed the upstream ridge during the past 36 h. This trough is amplifying and has a diffluent structure as it overtakes the eastern trough during the IOP. The Midwest trough has a large absolute vorticity maximum of greater than 16 X $10^{-5}s^{-1}$ and an organized area of positive vorticity advection over the upper Mississippi River Valley. The vorticity pattern is somewhat noisy in this analysis (computed from the analyzed NORAPS winds that are unsmoothed). However, the magnitude of the vorticity maximum agrees well with the NMC LFM analysis (not shown).

The diffluent structure of this trough is more evident in the upper troposphere. The 300 mb isotachs show a strong jet in the northwesterly flow with a 60 m s^{-1} jet maximum near 50°N, 110°W (Fig. 2.3). The 250 mb isotachs also show a strong jet in this location.

The second trough has a distinct surface system with a 1007 mb low pressure center over Wisconsin with a cold front extending southwestward to Texas (Fig. 2.2). There is a strong 1000-500 mb thickness gradient and a distinct cold advection zone behind the front. A warm front extends east of the Great Lakes cyclone to the New England states. These fronts and supportive 1000-500 mb thickness analyses show the main baroclinic zone in the eastern United States is associated with the second trough and extends through the Midwest rather than along the east coast of the United States.

The GOES visible sector at 1531 GMT (Fig. 2.4) indicates frontal cloudiness over Indiana, Illinois, Missouri and Arkansas. The GOES IR sector at 1201 GMT (not shown) suggests that the cloud tops are at the middle to high levels. Examination of surface observations for 1200 GMT indicates the cloudiness is mainly middle and high clouds with only minor precipitation activity. Shallow fog was the dominant weather reported in this area of frontal cloudiness, with continuous light drizzle reported in southern Indiana and Illinois at 1200 GMT. Satellite imagery shows large portions of Louisiana, east Texas and southeastern Oklahoma are blanketed by low stratus or fog, which agrees well with reported weather in those areas. There is little significant weather reported behind the cold front associated with the second trough. The overcast behind the front is reported to be predominantly stratocumulus and thick altocumulus, and does not extend more than 150 miles behind the front. The GOES IR sector from 1201 GMT (not shown) indicates a cyclonically curved high cloud band, associated with the Great Lakes cyclone, is located between Lake Michigan and James Bay.

One GALE aircraft flight is available to supplement the 1200 GMT observations (GALE, 1986). The King Air aircraft investigated the structure of a possible onshore jet at low levels associated with the first trough off the coast of South Carolina from 1306 to 1815 GMT 18 January 1986. The secondary mission was documentation of the marine boundary layer structure, turbulence and fluxes. Layered to patchy stratocumulus with isolated cumulus and light rainshowers were observed southeast of the North Carolina coast. Stratocumulus cloud bases ranged from 3500 to 4000 ft and tops ranged from 4000 to 5600 ft. Cumulus cloud tops were on the order of 9000 ft. No low-level wind maximum was observed. The King Air flew at 10,000 ft from Raleigh-Durham to 33.5°N, 77.5°W, descended in a stairstep pattern to 150 ft at 35°N, 75°W, then climbed to 10,000 ft before proceeding to 32.7°N, 74.3°W at constant altitude, and descended in a stairstep pattern to 150 ft at 33.5°N, 77.5°W, before returning to Raleigh-Durham at 10,000 ft. The two aircraft profiles are just to the northeast of a major line of convection along the Florida coast. Data from this mission can document the structure of the maritime southeasterly flow into the active convective region in advance of the first shortwave. The aircraft-derived vertical profiles can be used with CLASS rawinsondes to construct cross-sections through this system.

B. 0000 GMT 19 JANUARY 1986

During the second synoptic period of IOP 1, the Midwest shortwave begins to overtake the first trough as they both approach the east coast of the United States. The first trough and associated vorticity centers move from Louisiana to the southeast coast of the United States (Fig. 2.5). However, this trough has decreased in amplitude and the double vorticity maximum structure is still present. The maximum vorticity has decreased from 14 X $10^{-5}s^{-1}$ to 10 X $10^{-5}s^{-1}$, which agrees with the decreasing amplitude of the trough. The two centers in Georgia and Virginia support a weak PVA pattern along the east coast.

The sea-level pressure field changes substantially in the vicinity of this trough. Ridging from the North Atlantic anticyclone no longer extends to the Mississippi River Valley, but ends at the coast (Fig. 2.6). The increased southerly flow pattern intensifies warm air advection along the coast from Florida to New Jersey.

A distinct 50 m s^{-1} jet maximum at 300 mb is located east of South Carolina (Fig. 2.7). At 250 mb (not shown), the jet maximum associated with this system is also distinct and stronger (60 m s^{-1}). This represents a substantial strengthening of this jet streak in the past twelve hours. Both the 250 and 300 mb jet maxima are supported by five coastal rawinsonde observations from Florida to South Carolina. The 250 mb jet maximum is supported by three aireps over Florida, and the 300 mb jet maximum is supported by satellite wind observations at 28°N, 74°W and 32°N, 74°W. This NORAPS jet streak analysis is in agreement with a similar, but less intense intensification in the NMC 300 mb isotachs (not shown). This subtropical jetstream (STJ) intensification is similar (but more modest) to the jet behavior before the President's Day cyclone of 1979. Uccellini et al (1984) show a distinct strengthening of the STJ from 60 m s^{-1} to 80 m s^{-1} 24 to 36 h before that major cyclogenesis. In the President's Day cyclone, this maximum was also linked to an intensification of the low-level jet and associated low-level thermal and moisture advection along the coast. The increased temporal resolution of radiosonde data in this GALE case will aid in the study of these phenomena.

The GOES IR sector at 0031 GMT (Fig. 2.8) indicates a dramatic growth of the well-organized cloud mass with this system from Yucatan, across Florida and the Bahamas, and parallel to the east coast as far north as Virginia. Much of this cloud mass appears to be cirrus blow-off in an anticyclonically curved streak that extends southwest to northeast from the Yucatan to near 70°W off the east coast of the United

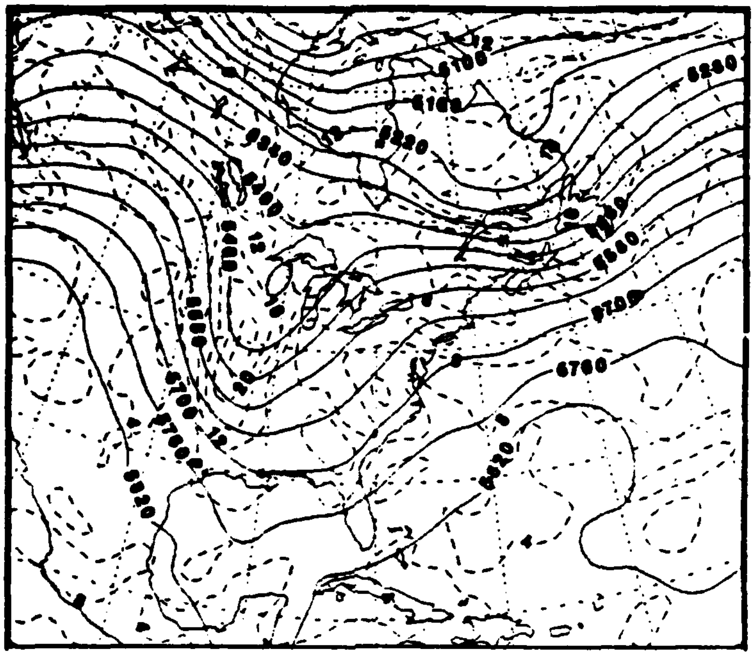

Figure 2.5 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) $10^{-5} s^{-1}$ valid 0000 GMT 19 January 1986.

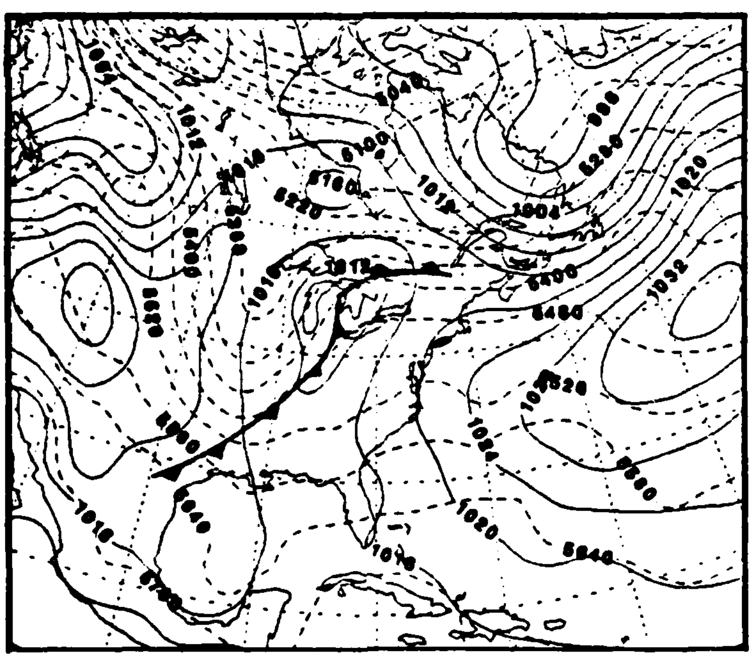

Figure 2.6 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 0000 GMT 19 January 1986.

States. The GOES water vapor imagery at 2331 GMT 18 January (not shown) indicates a dry slot curving northward across the Gulf of Mexico north of Yucatan to southeastern Georgia and coastal South Carolina consistent with 300 mb and 250 mb jet analyses. Satellite imagery indicates a region of lower cloud over northwestern Georgia, western North and South Carolina, and eastern Tennessee. An investigation of the surface observations from 0000 GMT indicates rain reported over this area of lower clouds. In addition, light precipitation activity is reported over central Florida under the jet streak clouds. Florida stations north and south of the rain area, as well as stations in Georgia and Alabama, are reporting shallow fog.

Although this East Coast perturbation appears weak in the surface and 500 mb synoptic analyses, it supports a large organized and precipitating cloud mass. The upper-level divergence inferred from the PVA and jet streak patterns appear to be coupled to the area of warm air advection in the low troposphere and is related to the well-organized cloud system.

Three GALE aircraft flights are available to supplement the 0000 GMT observations (GALE, 1986). These flights gathered data over and seaward of the Carolina coast in this cloud system. The NCAR Electra mapped marine boundary layer fluxes and obtained cross sections of state variables near the Carolina coast and over the Gulf Stream to investigate onshore transport of heat and moisture between 1700 and 2256 GMT 18 January 1986. Complex cloud structure was observed during this flight, with rainshowers of increasing intensity observed near 32°N, 77°W.

The NOAA P-3 investigated rainbands a short distance offshore from Hatteras during a flight between 2013 GMT 18 January and 0033 GMT 19 January. Light rainshowers without much organization were encountered, with most cloud tops less than 7000 ft, and a few tops to 10,000 ft.

A C-131 training mission flew from Raleigh-Durham to Hatteras in coordination with the NOAA P-3 from 2000 GMT 18 January until 0100 GMT 19 January. Scattered convective showers were observed enroute the coast and on the coast. Along flight legs at 12,000 ft, the aircraft was above the cloud tops. Flight-level data from these missions will allow an investigation of the onshore maritime flow and the possible presence of a low-level jet structure in response to upper-level jet streak intensification. The CLASS network coupled with this offshore aircraft data are well placed to study this shortwave system and the associated weather.

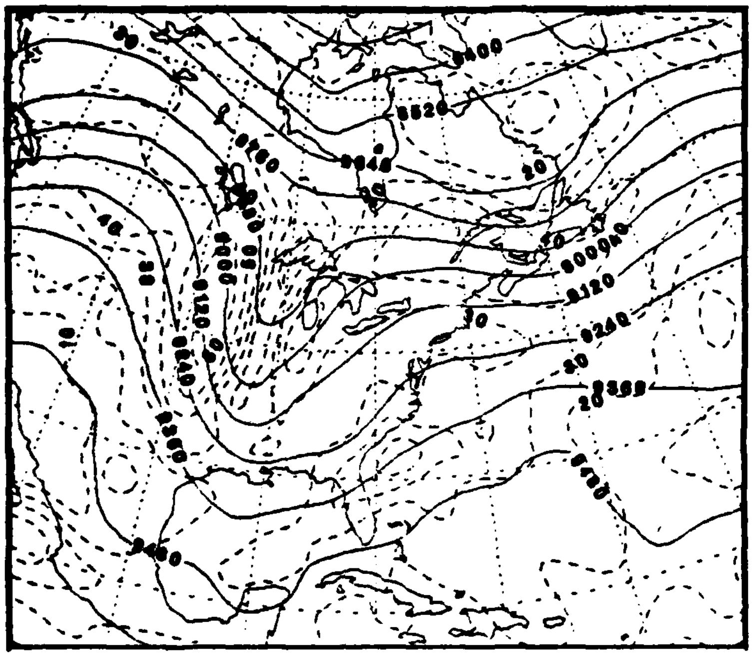

Figure 2.7 300 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 300 mb valid 0000 GMT 19 January 1986.

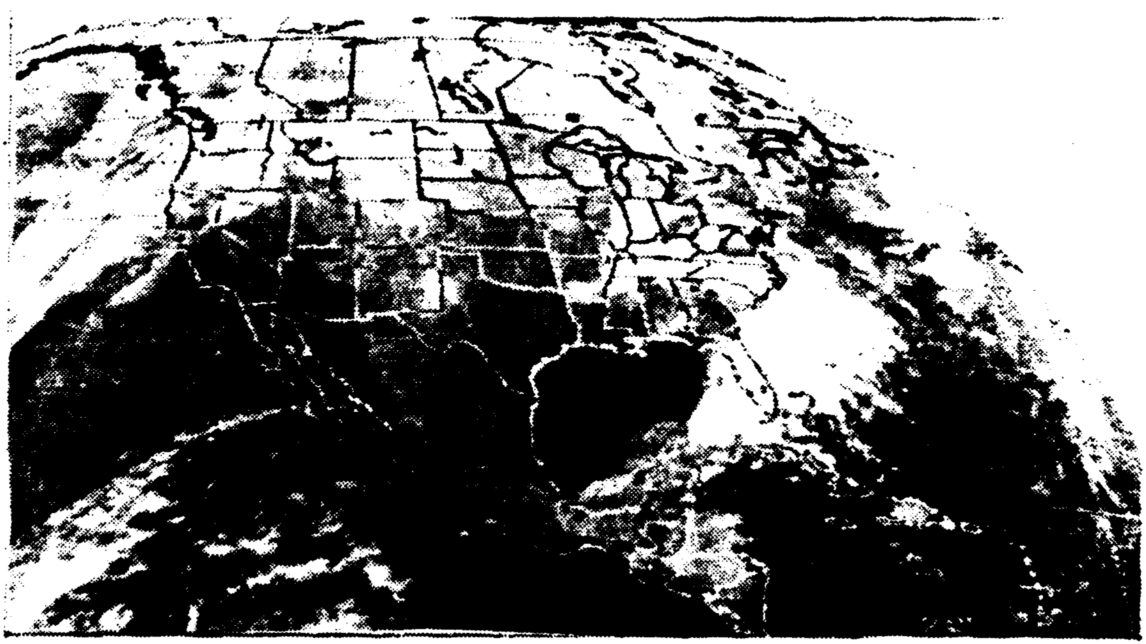

Figure 2.8 GOES satellite image valid 0031 GMT 19 January 1986.

The second trough continues its southeast movement and is now located over Missouri (Fig. 2.5). The vorticity maximum associated with the second trough has intensified significantly to $+24 \times 10^{-5} s^{-1}$. The 300 mb isotachs (Fig. 2.7) show a 60 m s^{-1} jet maximum located in the northerly flow upstream of the 500 mb trough axis. The 300 mb trough remains strongly diffluent downstream of the trough axis.

The 1000-500 mb thickness analysis (Fig. 2.6) indicates a strong temperature gradient and intense cold advection over the Mississippi River Valley coupled to the amplifying upper-air trough. The low pressure center over Wisconsin 12 h earlier has moved east over Lake Huron and weakened as the upper-air support moved southeastward. The NMC final sea-level pressure analysis (not shown) indicates a new secondary 1008 mb low center developing over Kentucky. This low center subsequently becomes one of the most significant surface features of IOP 1. The NORAPS analysis only indicates a trough in the vicinity of the new low. The related cold front extends southwestward from the primary center over the Great Lakes through the secondary center into east Texas.

The GOES IR imagery at 0031 GMT (Fig. 2.8) indicates an organized cloud pattern developing over Indiana and southern Illinois that is associated with the 500 mb PVA pattern. Continuous light to moderate rain behind the cold front is reported in this area. The GOES water vapor imagery at 2331 GMT 18 January (not shown) indicates that the polar jetstream associated with the second trough curves across southern Canada and then southward over eastern Minnesota. A pool of relatively dry mid-tropospheric air is also noted over Missouri and northwestern Arkansas.

This Midwest trough is an excellent example of a developing shortwave in the large-scale northwesterly flow. The cold air advection under the trough axis and the warm air advection to the east contributes to amplifying the upper tropospheric wave. The new secondary low is supported by the positive vorticity advection pattern of the upper-level trough and the strong lower tropospheric frontal zone. When available, the 3-h NWS rawinsondes during this 12-h period should provide a more detailed examination of this rapidly-amplifying shortwave.

C. 1200 GMT 19 JANUARY 1986

During the next 12 h the Midwest trough starts to merge with the coastal trough (Fig. 2.9). The first trough now extends southeastward from the Carolina coast and is still evident in the 500 mb vorticity analysis. The double vorticity center structure has

moved northeastward to North Carolina and Maryland and weakened substantially. The area of very weak positive vorticity advection associated with these maxima extends from the Carolinas northeastward to southern New England.

The NORAPS sea-level pressure analysis shows a low center with a broad 1008 mb closed isobar centered over West Virginia, and troughing to the Carolina coast associated with the first trough (Fig. 2.10). At this time the NMC analysis (not shown) indicates a warm and cold frontal wave structure is located along the East Coast, with the peak of the wave located over coastal North Carolina (Fig. 2.10). In addition there is a large amount of cloudiness associated with the first shortwave. The baroclinic structure of the first shortwave parallels the East Coast with a distinct thermal ridge over the Mid-Atlantic States. The warm air advection pattern east of this thermal ridge is quite intense with a strong southerly flow directed toward the New England states.

At 300 mb (Fig. 2.11) and 250 mb (not shown), one jet maximum is analyzed seaward of the Georgia coast and a second is east of the Maryland coast. The magnitudes of the maxima (40 m s^{-1} at 300 mb and 50 m s^{-1} at 250 mb) are less than 12 h earlier. The northern maximum represents the northeastward movement of the Georgia coast jet streak from 12 h earlier. The NORAPS 300 mb analysis is supported by the Bermuda rawinsonde observation and the 250 mb jet maximum in the same area is supported by two strategically located aireps and the Bermuda rawinsonde observation.

The GOES visible sector at 1331 GMT (Fig. 2.12) shows strong, well organized, convective activity along the coast in the area of the fronts. The shadows in this early morning image clearly delineate the boundary of high clouds curving cyclonically from Lake Okeechobee to coastal North Carolina. Blow-off from the high cloud tops curve anticyclonically about an axis along 75°W. Anticyclonic bulging in the cloud mass over eastern North Carolina and Virginia indicates that surface wave formation is occurring in agreement with the sea-level pressure analysis. The GOES water vapor image at 1131 GMT (not shown) indicates that the dry slot associated with the STJ has migrated eastward and is located across central Florida and seaward of Georgia and South Carolina.

Examination of the surface observations at 1200 GMT indicates fog and continuous light rain reported over coastal North and South Carolina and Georgia, and as far north as New Jersey and Pennsylvania. The predominant cloud type reported is fractostratus or fractocumulus ("scud").

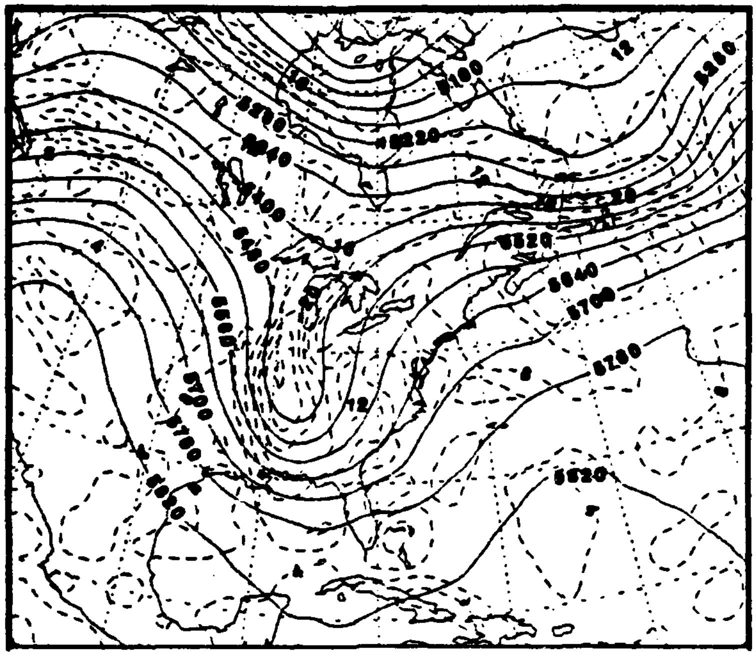

Figure 2.9 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) 10^{-5} s^{-1} valid 1200 GMT 19 January 1986.

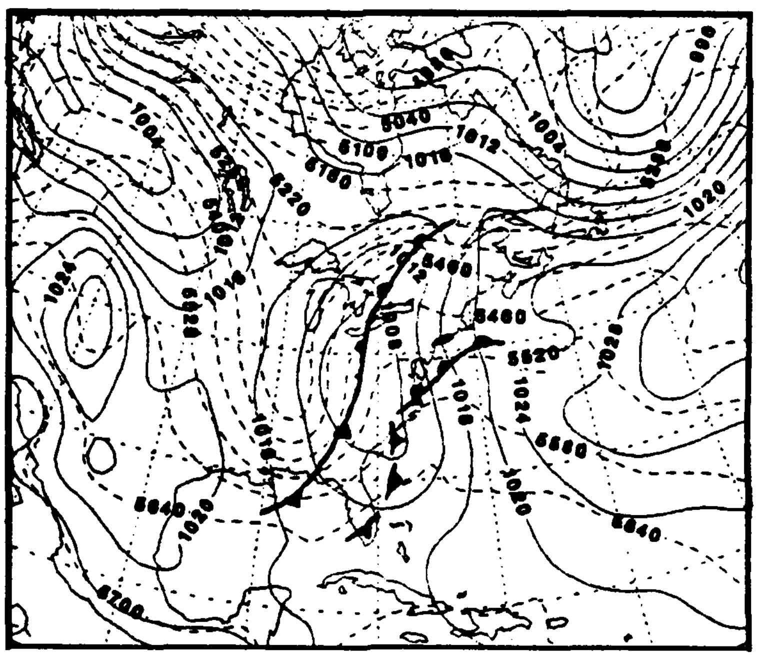

Figure 2.10 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 1200 GMT 19 January 1986.

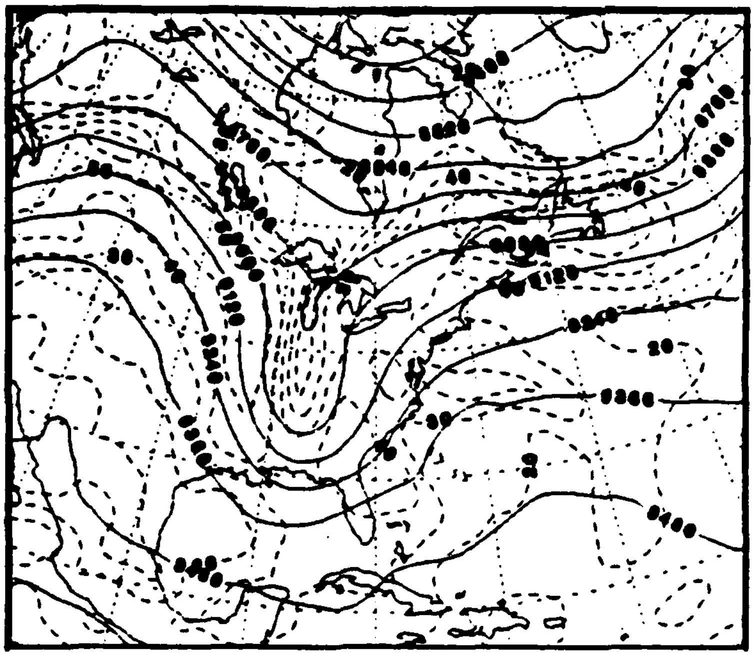

Figure 2.11 300 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 300 mb valid 1200 GMT January.

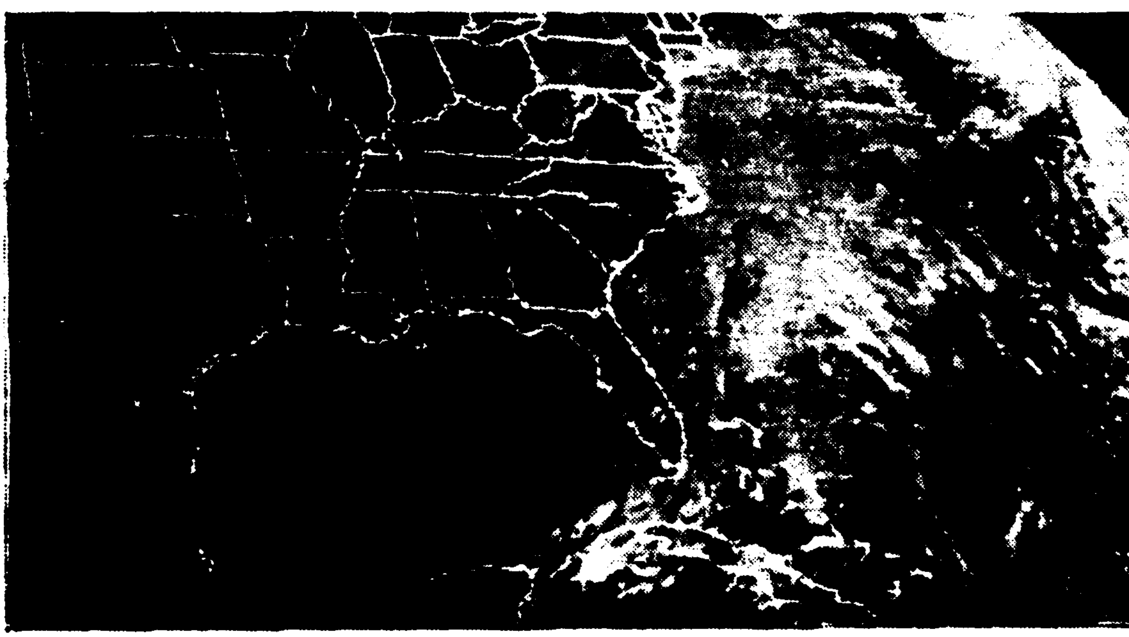

Figure 2.12 GOES visible satellite image valid 1331 GMT 19 January 1986.

One GALE aircraft flight is available to supplement the 1200 GMT observations of the first trough in IOP 1 (GALE, 1986). The King Air aircraft investigated the onshore jet and marine boundary layer between 1402 and 1824 GMT on 19 January. During this flight, the aircraft overflew the RV Cape Hatteras in order to compare measurements. The flight path extended southeastward from Raleigh-Durham to 33.5°N, 77.5°W and then a rectangle was flown that extended as far east as 76°W and as far south as 32.5°N. Layered stratus and stratocumulus were observed with heavy rain at 34°N, 76.5°W, and light rainshowers at 33.5°N, 77.5°W. Winds were strong (15-25 m s^{-1}) throughout the boundary layer, but little evidence of a strong wind maxima was found.

Looking westward, the second trough continues to amplify at 1200 GMT 19 January 1986 (Fig. 2.9). It has moved eastward to 87°W during the preceding 12 h (Fig. 2.9). The area of strongest positive vorticity associated with the second trough is now near the trough axis, which produces NVA west of the 500 mb trough axis and PVA downstream of the axis.

The NMC sea-level pressure analysis (not shown) indicates the primary low center over the Great Lakes has filled while the secondary low center originally over Kentucky has moved over West Virginia and deepened 5 mb to 1003 mb. This preferential deepening coincides with the arrival the second trough and associated vorticity maximum upstream of the secondary center. The West Virginia cyclone position represents a compromise between the vorticity advection processes to the south and the thermal advection activity associated with the first system to the north and east. Deepening of the surface low center over West Virginia results in more southerly flow and stronger warm advection from coastal North Carolina to New Jersey, as discussed above. The cold front associated with the second trough moves southeastward and extends across eastern Tennessee, Georgia and the panhandle of Florida.

The amplitude of the second short-wave trough also increases in the upper troposphere (Fig. 2.11). A strong jet is still present in the northwesterly flow. The magnitude of the jet at both 300 mb and 250 mb is somewhat weaker than 12 h earlier, with maximum winds of 50 m s^{-1} at 300 mb west of the trough line.

The cold front across eastern Tennessee, Georgia and the panhandle of Florida appears weak and disorganized on the GOES IR data at 1231 GMT (not shown). This front, with strong westerly winds aloft, is similar to other fast moving fronts with no

significant weather at the front and more active weather to the east. The GOES water vapor imagery at 1131 GMT (not shown) indicates that the pool of relatively dry mid-tropospheric air has migrated from Missouri southeastward over Tennessee and northern Alabama in the past 12 h. The new position corresponds with the 500 mb trough position and the area of strong NVA into the trough axis. The polar jetstream associated with the second trough is now much harder to discern on the water vapor imagery.

Two GALE aircraft flights are available to supplement the 1200 GMT observations of the second trough (GALE, 1986). A Sabreliner flight investigated the mesoscale structure within an apparent upper-level tropopause fold between 0917 and 1617 GMT 19 January. The flight traveled from Raleigh-Durham to Nashville to Memphis and returned to Raleigh. Onboard observers documented a well-defined upper-level front and fold indicated by strong wind and temperature gradients and high ozone concentrations. The mission included detailed cross-sections at approximately 16,000, 20,000, 24,000, 31,000, and 35,000 feet from Nashville TN southwestward to 35°N, 87.5°W. However, the aircraft mission description does not describe where, or at what level, the upper-level front and tropopause fold were observed. Further investigation into this flight should provide important information on the location and strength of the front and tropopause fold associated with the second trough. This detailed aircraft data can be inter-compared with the 3-h rawinsondes as the upper front intensifies.

The NOAA P-3 investigated the storm structure upwind of the GALE inner area between 1234 and 1750 GMT 19 January to help define initial conditions for mesoscale predictions for the GALE inner area. An upper front was encountered at 547 mb over southeastern South Carolina. During transects lower in the troposphere in western South Carolina onboard observers documented frontal zones at 840 and 692 mb. These modest frontal zones are part of the first shortwave system as the first shortwave and cold front are over the Appalachians at this time. Clouds ranged from moderate cumulus to small layers of stratiform clouds near the front, although with substantial time and space variation. Convective activity was modest. Low-level moisture appeared to be converging into heavier showers in the mountains of western North Carolina.

D. 0000 GMT 20 JANUARY 1986

By 0000 GMT 20 January, the two short-wave 500 mb troughs have merged (Fig. 2.13). The second trough has developed into a 500 mb closed circulation with a central height below 540 dm over western North Carolina. The first trough axis now extends offshore southeastward from Virginia and the Carolinas. The positive vorticity maximum associated with the first trough is located off the North Carolina and New England coasts in advance of the trough axis. The NORAPS analysis of the first trough is supported by temperature profiles from four satellite observations, the rawinsonde from Bermuda, and two oceanic rawinsonde observations in the FNOC data base. While the trough is less pronounced in the LFM analysis (not shown), the vorticity pattern is similar in magnitude and distribution.

The NORAPS sea-level pressure analysis shows a low pressure center located over Washington DC, with troughing along the Carolina coast (Fig. 2.14). On the NMC analysis, a cold front associated with a frontal wave curves southwestward to southern Florida, while a warm front extends along the coast to Newfoundland. An area of enhanced cloud activity along 70°W in the GOES IR sector at 0130 GMT (Fig. 2.15) is now analyzed as a trough on the NMC analysis. Continuity and satellite images indicate this trough is the front previously along the coast from Cape Cod to North Carolina which moved eastward to 70°W. This area of enhanced cloudiness off the Carolina coast has presented surface analysis problems for NMC during the entire IOP. After first not being analyzed and then labeled a cold and warm frontal wave, it is now analyzed as a trough. The large cloud band with its shortwave support is one of the most interesting aspects of IOP 1.

The 300 mb isotachs show a 50 m s^{-1} maximum that extends from Chesapeake Bay to Long Island in the southerly flow downstream of the trough axis (Fig. 2.16). Isotherms and height contours are in phase and symmetrical from 500 mb to 300 mb (not shown), which indicates weaker upper-level baroclinicity above 500 mb.

The axis of the second trough is now located over Florida directly south of the closed 500 mb center, with a $+24 \times 10^{-5} s^{-1}$ vorticity maximum over South Carolina. The vorticity maximum over South Carolina is providing PVA along the East Coast from North Carolina to New Jersey.

The merging of the two short-wave troughs is reflected at the surface by the development of a double centered low pressure area. The NMC sea-level pressure analysis indicates that the low over West Virginia has moved northeastward to

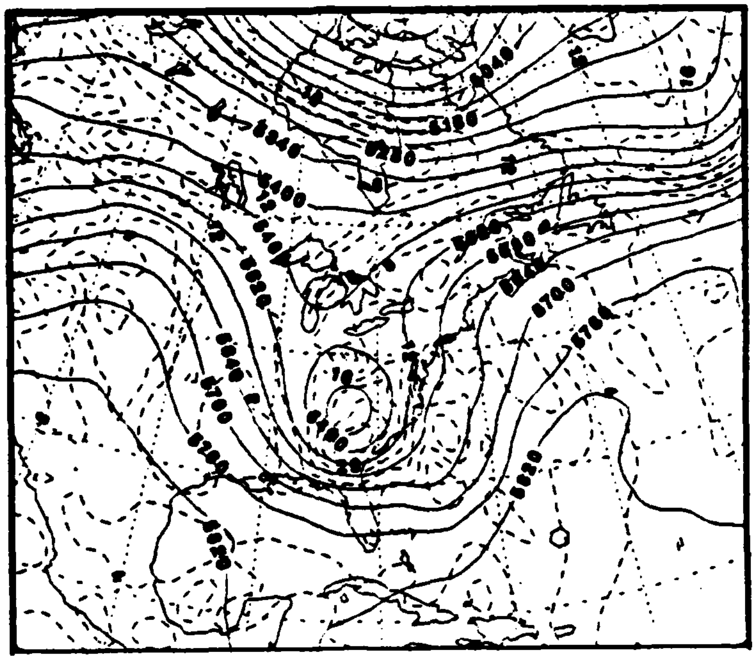

Figure 2.13 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) $10^{-5}\ s^{-1}$ valid 0000 GMT 20 January 1986.

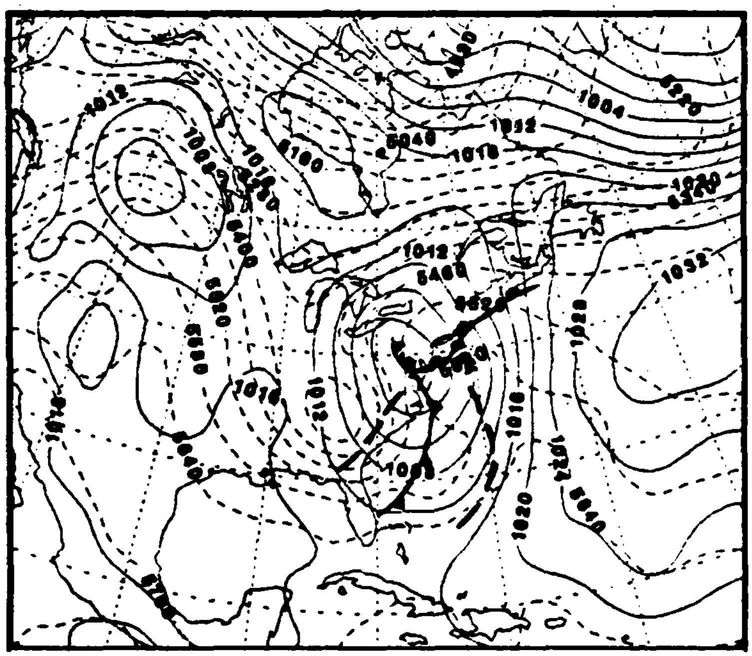

Figure 2.14 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 0000 GMT 20 January 1986.

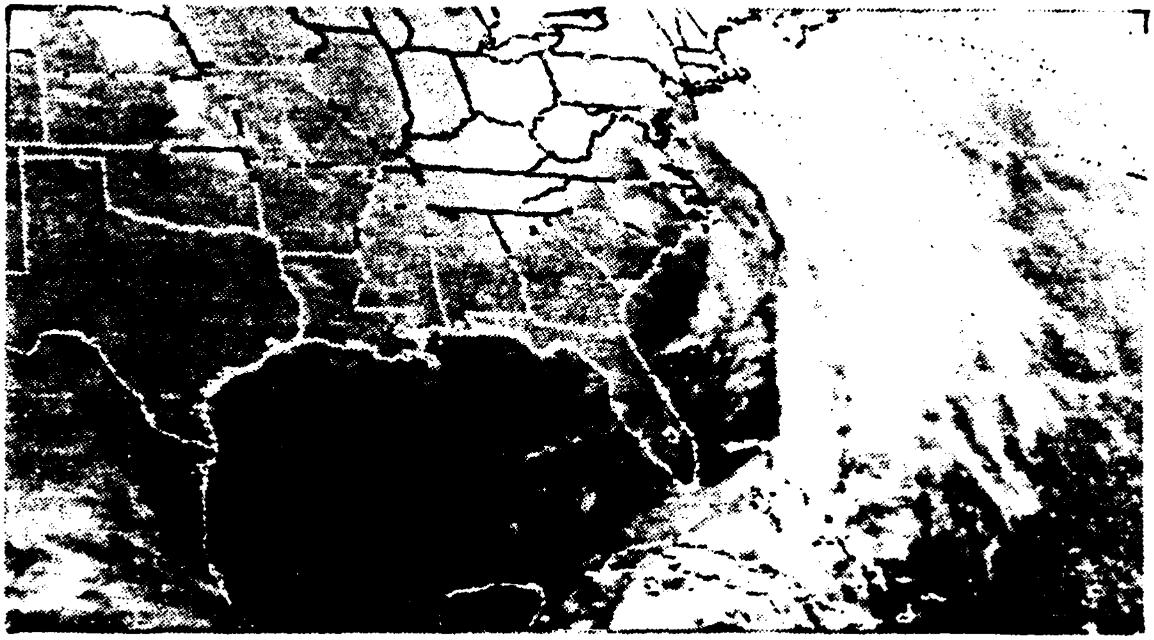

Figure 2.15 GOES infrared satellite image valid 0130 GMT 20 January 1986.

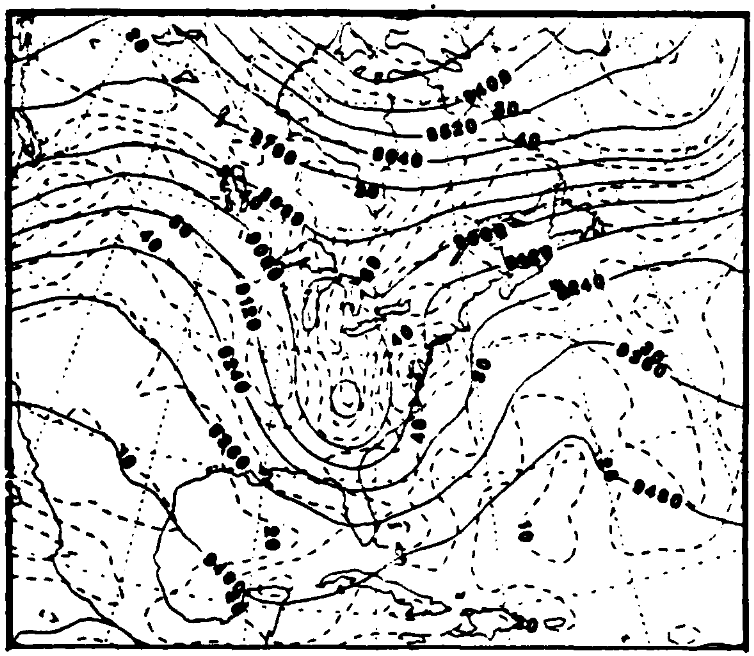

Figure 2.16 300 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 300 mb valid 0000 GMT 20 January 1986.

Pennsylvania, deepened and merged with troughing in the southerly flow off North Carolina to form this dual low which appears as an elongated center in the NORAPS analysis (Fig. 2.14). The second center is located over Washington, D.C.. The pressure gradient between the low over Washington, D.C. and the North Atlantic ridge has strengthened and intensified the low-level southerly flow and warm advection east of 70°W. The cold front associated with the second trough has moved rapidly eastward and now curves southeastward from Washington, D.C. to the Virginia Capes, and then southwestward toward Lake Okeechobee.

The GOES IR sector at 0130 GMT (Fig. 2.15) indicates a weakly organized band of low-level and mid-level clouds in the general location of the cold front associated with the second trough. The satellite imagery also shows a strong band of organized cloudiness curving cyclonically from central Cuba northward to New England which coincides with the surface trough analyzed along 70°W (Fig. 2.14). This feature appears to consist of two parallel bands of cloudiness separated by a relatively clear area. Strong cirrus blow-off is confined predominantly to the easternmost cloud band. An earlier GOES visual sector from 1931 GMT (not shown) indicates that the westernmost band of clouds consists mainly of cirrus. The GOES water vapor imagery at 2331 GMT 19 January (not shown) indicated that the dry slot west of the cirrus band associated with a southerly branch of the STJ continued to migrate eastward, and now passes between Florida and Cuba and curves northward to 35°N where cirrus blowoff indicates it curves southward again. The water vapor imagery also indicates that the pool of relatively dry mid-tropospheric air is now a symmetrical donut shape located over western North Carolina. This corresponds well with the position of the 500 mb cut-off low center.

Three GALE aircraft flights are available to supplement the 0000 GMT observations (GALE, 1986). Each of the flights penetrated a squall line located over the Gulf Stream along 75°W at 2101 GMT in the GOES visual image (not shown). This convective line developed east of the cold front but west of the main cloud system. The NCAR Electra mapped the structure of the onshore flow associated with onshore cyclogenesis and detected horizontal moisture and heat transport onshore between 1900 GMT 19 January and 0144 GMT 20 January. Flying from Raleigh-Durham east-southeastward to 33.5°N, 74°W, a cumulus and stratocumulus overcast with haze was observed at the coast. Cumulus congestus at the coast became cumulonimbus over the Gulf Stream, with lightning flashes, strong turbulence and moderate rainshowers.

The NOAA P-3 conducted a cold front and Gulf Stream rainband study between 2000 GMT 19 January and 0212 GMT 20 January. The primary data collection area was east of Hatteras between 34°N and 36°N and between 73°W and 75°W. Strong, mainly convective, precipitation was encountered with abundant lightning.

The C-131 conducted rainband measurements in coordination with the NOAA P-3 between 2000 GMT 19 January and 0135 GMT 20 January. The aircraft flew at 14,000 ft above the cumulus from Raleigh-Durham to Cape Hatteras. A few cumulonimbus were observed along the flight path with tops to 20,000 ft. The aircraft penetrated a small rainband just onshore from Cape Hatteras and a more imposing squall line on the edge of the Gulf stream. The Gulf Steam squall line produced heavy precipitation (small hail), anvil tops (30,000 ft), and heavy lightning (aircraft struck twice).

The reports from the aircraft flights correlate well with an area of enhanced convection over the Gulf Stream southeast of the Carolina coast. The GOES visual sector at 1931 GMT (not shown) indicates a linear area of enhanced convection extending southward from Cherry Point, North Carolina to 31°N, 77°W.

For the past nine hours, the CLASS rawinsonde sites and the NWS station at Petersburg, VA have been launching at 90-minute intervals. The preceding nine hours should provide a detailed picture of the three-dimensional temperature and moisture structure of this surface and upper tropospheric frontal activity with vigorous 500 mb closed cyclone. Not coincidentally, this is also one of the most interesting and active periods of the IOP. During this period, the cold front crosses the GALE inner area, the 500 mb circulation cuts off directly to the west, and a 60 m s^{-1} jet maximum develops over the northern GALE regional area.

Two vertical cross-sections of potential temperature (θ) were constructed to reveal the location and structure of the upper front, the first (Fig. 2.17) from Peoria, Illinois to West Palm Beach, Florida (Fig. 2.18) and the second (Fig. 2.19) from Monet, Missouri to Cape Hatteras, North Carolina (Fig. 2.20). These cross-sections transect the closed 500 mb low along east-west and north-south lines as indicated in Figs. 2.17 and 2.19. Both cross-sections clearly indicate the presence of the cold dome associated with the cut-off low over western North Carolina. The Monet-Hatteras cross-section shows the cold dome west of Greensboro. The Peoria-West Palm Beach cross-section places the center of the cold dome over Athens, Georgia, which agrees with the 500 mb analysis (Fig. 2.13). The upper front is depicted clearly in the Peoria-

West Palm Beach cross-section and slopes from 500 mb to 750 mb south of Athens, Georgia. The inversion continues southward to West Palm Beach at 750 mb. The Athens, Georgia rawinsonde (Fig. 2.21) indicates a 500 mb tropopause with conditional instability from the surface to the tropopause and significant moisture to 700 mb. The Waycross, Georgia rawinsonde (Fig. 2.22) shows a frontal inversion based at 800 mb that extends to 600 mb, and a 350 mb tropopause. The wind backs slightly and increases from 15 m s^{-1} to 35 m s^{-1} through the inversion.

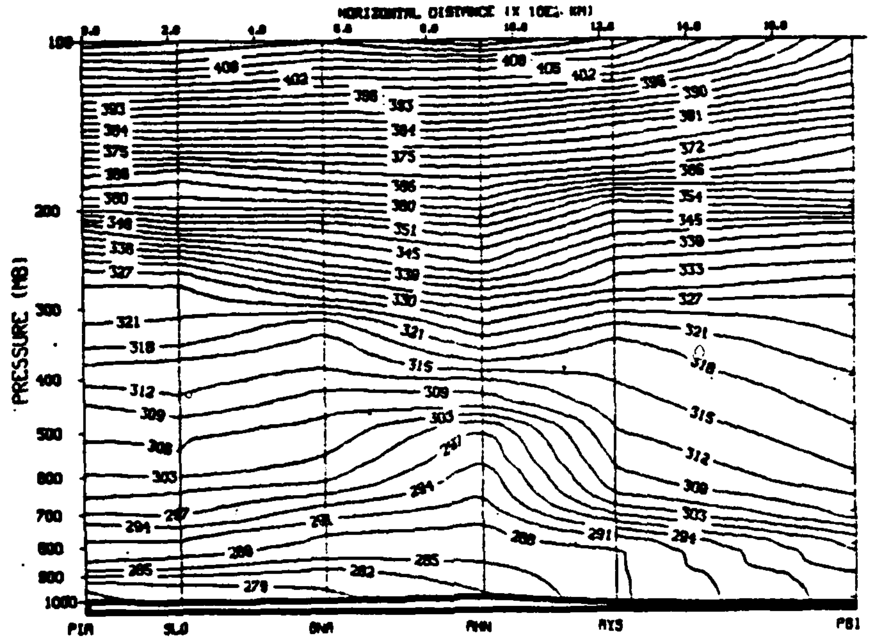

Figure 2.17 Vertical cross-section of potential temperature (θ) through Peoria IL, Salem IL, Nashville TN, Athens GA, Waycross GA and West Palm Beach FL, valid 0000 GMT 20 January 1986.

The east-west cross-section from Monet, Missouri to Cape Hatteras also captures the upper front east of Greensboro, North Carolina. However, the frontal inversion weakens as it approaches the coast. The Nashville, Tennessee rawinsonde (Fig. 2.23) shows a complex pattern of inter-leaving moist and dry layers from the surface to 500 mb. Two frontal inversions are probable at 850 mb and at 700 mb. These potential temperature cross-sections indicate a tropopause fold sloping southeastward into the mid to low troposphere near the Carolina coast. This strong upper and mid-level organization occurs without significant low-level cyclogenesis, which may suggest that a favorable low-level environment is important for sea-level cyclogenesis.

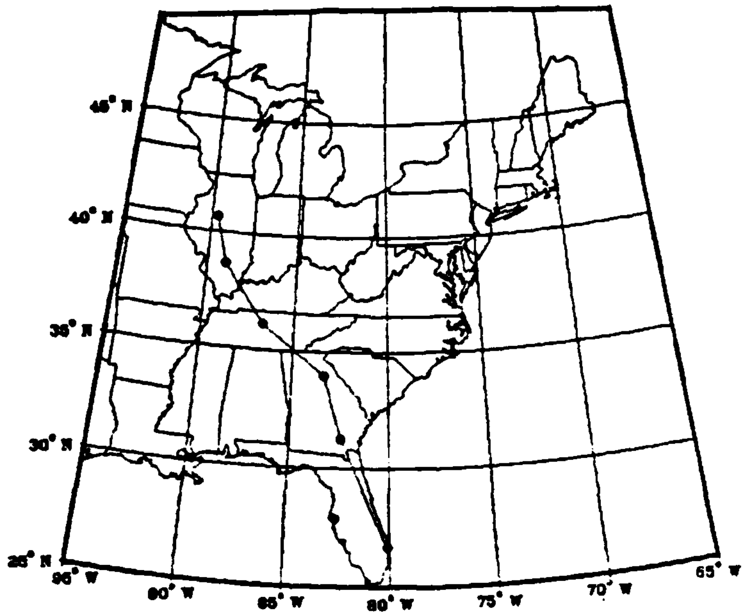

Figure 2.18 Location of vertical cross-section of potential temperature (θ) through Peoria IL, Salem IL Nashville TN, Athens GA, Waycross GA and West Palm Beach FL.

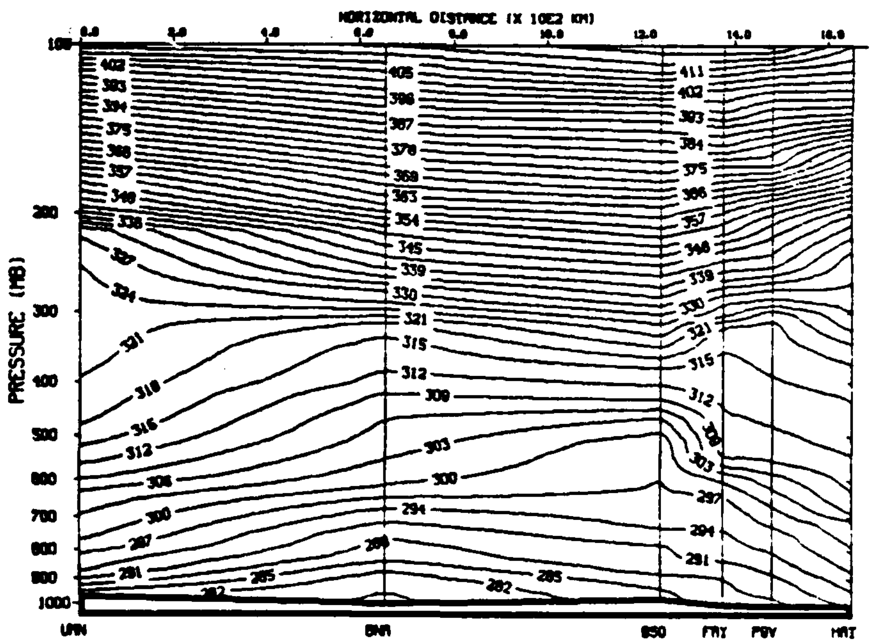

Figure 2.19 Vertical cross-section of potential temperature (θ) through Monet MO, Nashville TN Greensboro NC, Fayetteville NC Petersburg NC, and Cape Hatteras NC, valid 0000 GMT 20 January 1986.

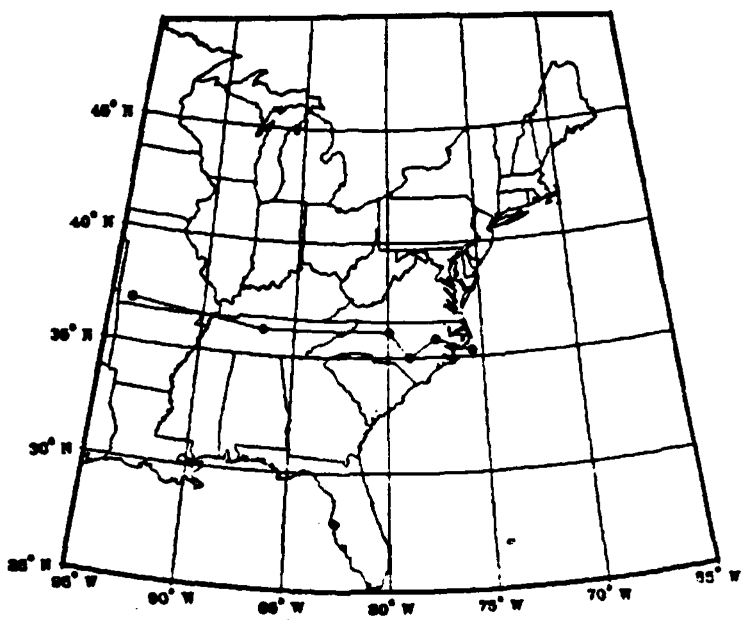

Figure 2.20 Location of vertical cross-section of potential temperature (θ) through Monet MO, Nashville TN Greensboro NC , Fayetteville NC, Petersburg NC and Cape Hatteras NC.

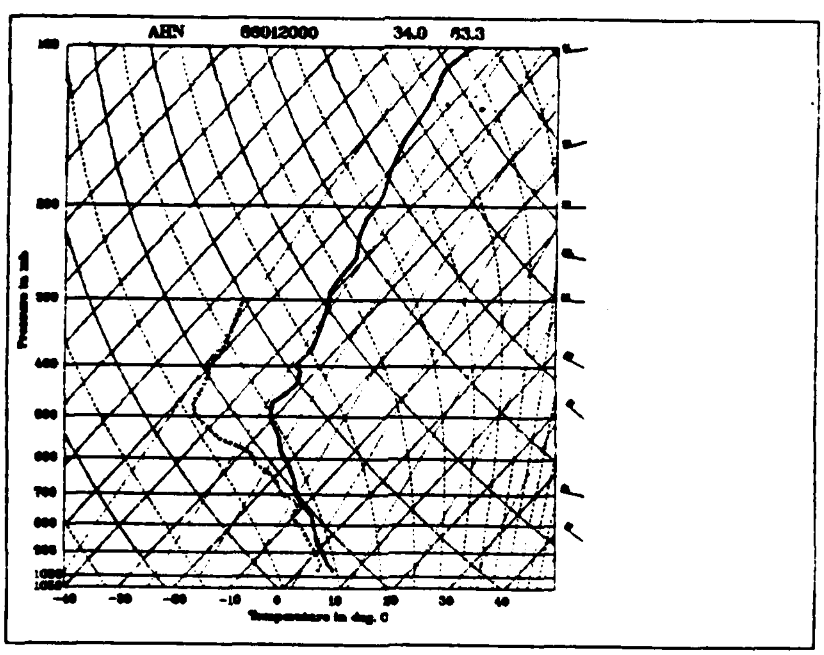

Figure 2.21 Rawinsonde for Athens GA valid 0000 GMT 20 January 1986. Pressure in mb, temperature in °C, wind in kt.

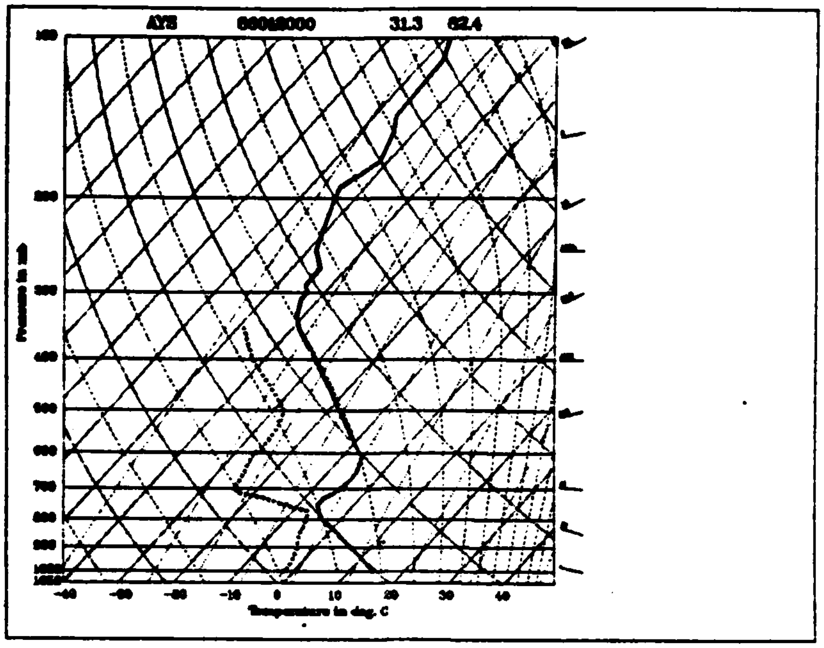

Figure 2.22 Rawinsonde for Waycross GA
valid 0000 GMT 20 January 1986.
Pressure in mb, temperature in °C, wind in kt.

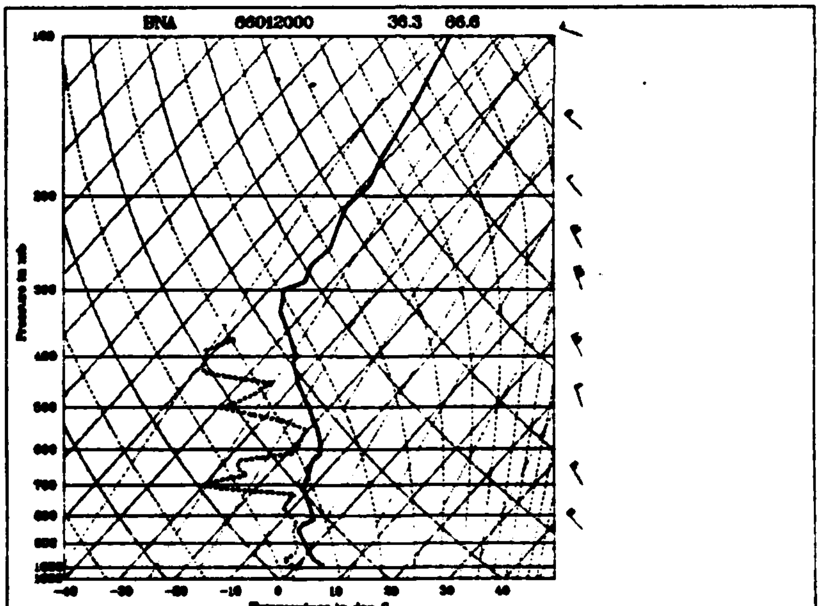

Figure 2.23 Rawinsonde for Nashville TN
valid 0000 GMT 20 January 1986.
Pressure in mb, temperature in °C, wind in kt.

E. 1200 GMT 20 JANUARY 1986

During the fifth synoptic period of IOP 1, the 500 mb closed circulation moves northeastward to the Chesapeake Bay with little change of intensity (Fig. 2.24). A strong vorticity center ($+26 \times 10^{-5} s^{-1}$) is now symmetrical around the closed center. The NORAPS 500 mb vorticity analysis shows several maxima south and east of the closed circulation. While the NMC vorticity analysis (not shown) is somewhat smoother, the location and magnitude of vorticity maxima support the NORAPS analysis.

The sea-level pressure analysis at 0600 GMT indicates the low over Pennsylvania merged with the low over Washington, D.C. to form a single center over southeastern Pennsylvania. This center moved slowly northward to eastern New York and deepened to 989 mb by 1200 GMT (Fig. 2.25). The cyclone still retains an asymmetric structure due to the troughing along the warm front associated with warm air advection.

The cold front associated with the second trough has propagated rapidly eastward to overtake the trough analyzed at 70°W 12 h previously. The cloudiness associated with the trough is further enhanced by the strong baroclinicity of this new cold surge. The 1000-500 mb thickness indicates strong baroclinity behind the cold front (Fig. 2.25) with the strongest low-level cold advection in the southeast quadrant of the cyclone. The 300 mb isotachs (Fig. 2.26) show a 50 m s^{-1} jet streak located over the Carolina coast.

The GOES visual sector at 1331 GMT (Fig. 2.27) shows a strong low-level cold outbreak, with narrow cloud lines off the coast extending from Florida to North Carolina that curve cyclonically northward. The leading edge of the cold surge consists of a narrow, organized line of convection. In advance and parallel to the cold surge convection is a well organized cold frontal band of cloudiness with strong vertical development and cirrus blow-off. A spiral pattern is evident in the clouds over eastern Pennsylvania that corresponds to the location of the mature vortex, with a dry slot between 70°W and 75°W.

F. 0000 GMT 21 JANUARY 1986

During the last synoptic period of IOP 1, the 500 mb closed circulation (534 dm central contour) moves northeastward over Massachusetts (Fig. 2.28). At this time, the 500 mb closed circulation is vertically located above the surface cyclone (Figs. 2.29 and 2.28). A short-wave trough now extends southward along 70°W from the closed

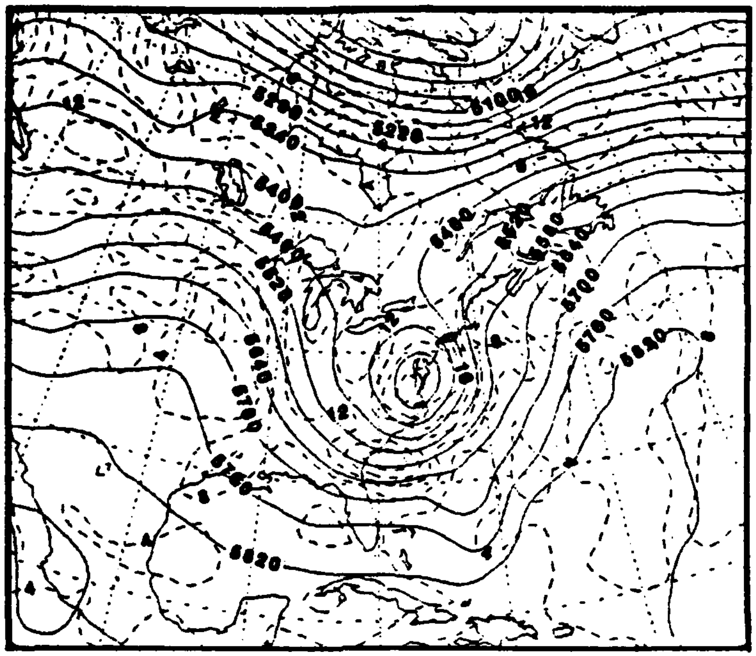

Figure 2.24 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) $10^{-5} s^{-1}$ valid 1200 GMT 20 January 1986.

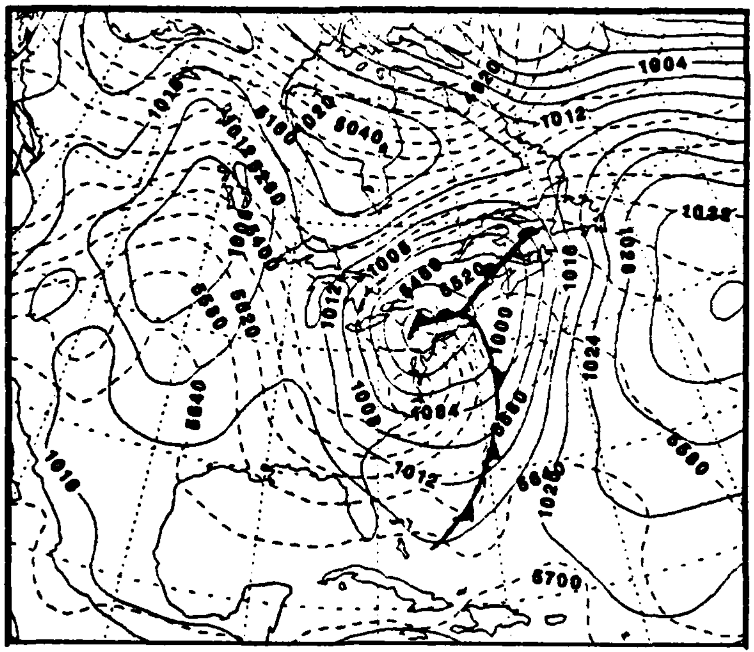

Figure 2.25 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 1200 GMT 20 January 1986.

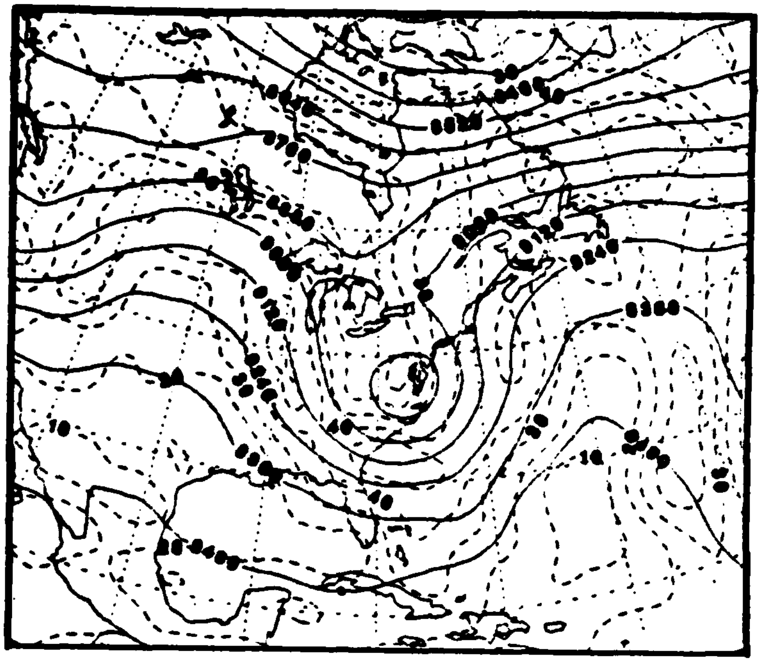

Figure 2.26 300 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 300 mb valid 1200 GMT 20 January 1986.

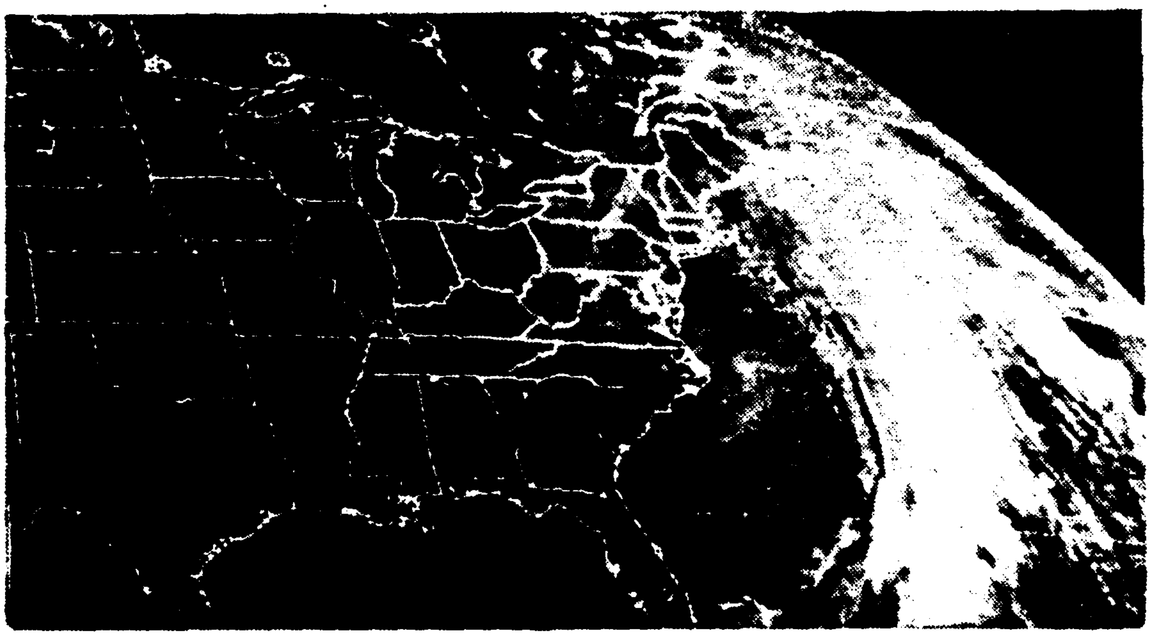

Figure 2.27 GOES infrared satellite image valid 1331 GMT 20 January 1986.

500 mb circulation. The NMC analysis places the second trough somewhat farther west along 75°W (not shown).

The NORAPS sea-level pressure analysis places the 989 mb sea-level low pressure center over New Hampshire. It has filled 3 mb in the previous 12 h. The cyclone's cold front curves southeastward from Maine to 64°W and then southward and southwestward to Cuba. The NMC frontal analysis was not available for 0000 GMT 21 January 1986. Strong low-level southerly flow and warm advection are indicated between 55°W and 65°W.

The 300 mb analysis indicates that the upper-level cyclone center is nearly coincident with location of the surface system (Fig. 2.30). The 300 mb isotachs show a 60 m s^{-1} jet maximum in the southeast quadrant of the cyclone.

The dry slot apparent on the GOES IR sector at 2001 GMT 20 January (Fig. 2.31) indicates cold air has wrapped almost completely around the surface cyclone. The strong, well organized, and cyclonically curved cold frontal cloud band continues to move eastward. The convective activity in the cold air behind the front has shifted from narrow open cell cloud lines to predominantly closed cellular cloudiness. Enhanced convection is observed in the vicinity of 40°N, 70°W. There were no GALE aircraft flights to investigate this synoptic period as the storm moved into the Canadian Atlantic Storms Project (CASP) network.

G. VERIFICATION OF NORAPS PROGNOSES FOR IOP 1

The NORAPS predictions are based on the 0000 GMT 19 January 1986 analyses and are verified against the analyses previously discussed. The prognoses of the meteorological fields are available in 6-h increments to 48 h. The prognoses are analyzed at 12-h increments beginning with the 12 h forecast. Valid time (VT) is the the time for which a forecast is valid. The analysis time was chosen to span the significant deepening of the IOP 1 cyclone. The goal of this validation is to document the ability of NORAPS with operationally available data to forecast the details of the IOP 1 case. This validation will serve as a control for future forecast experiments using GALE data.

1. 12 h prognosis VT: 1200 GMT 19 JANUARY 1986

Significant errors that eventually produce an important impact on the forecast are evident as early as 12 h into the forecast. At 500 mb, the amplifying trough was forecast in the correct position (Fig. 2.32), but the forecast was 60 m weaker than the

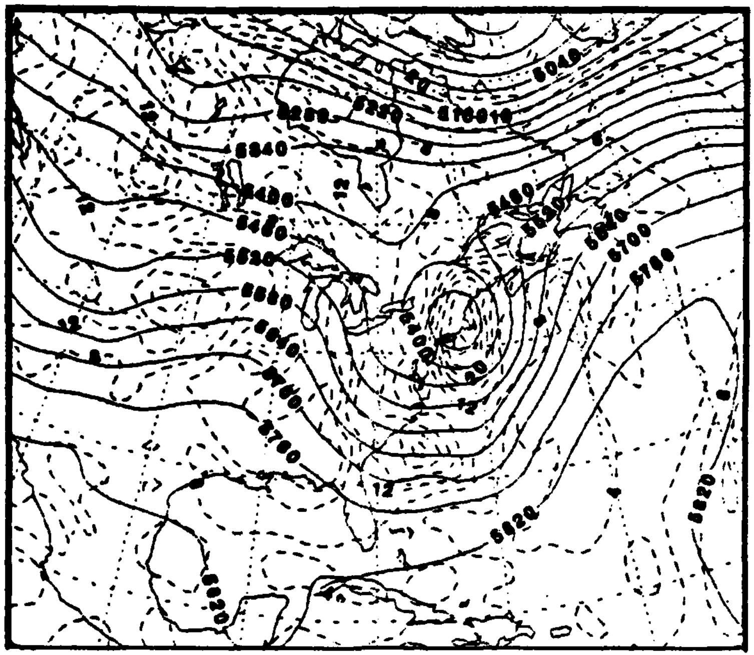

Figure 2.28 500 mb geopotential height analysis (solid) m
and vorticity analysis (dashed) $10^{-5} s^{-1}$
valid 0000 GMT 21 January 1986.

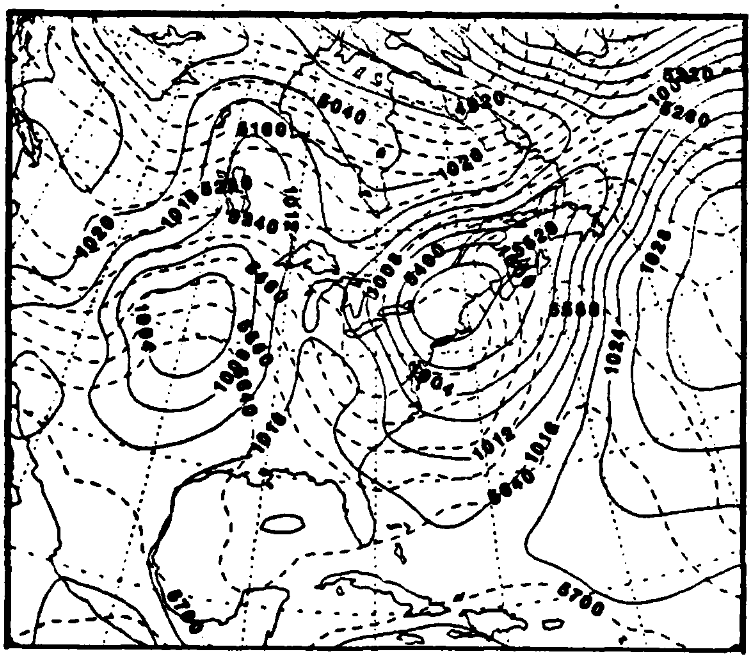

Figure 2.29 Sea-level pressure analysis (solid) mb
and 1000-500 mb thickness (dashed) m
valid 0000 GMT 21 January 1986.

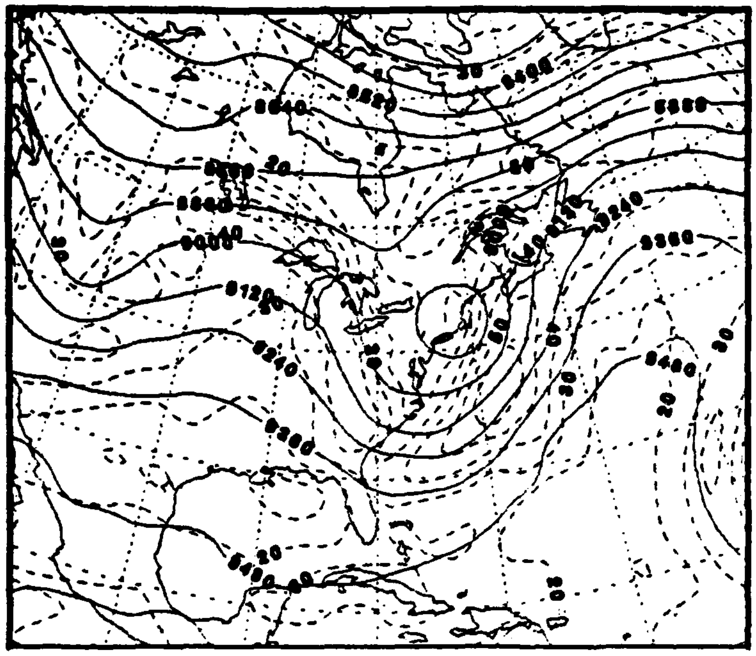

Figure 2.30 300 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 300 mb valid 0000 GMT 21 January 1986.

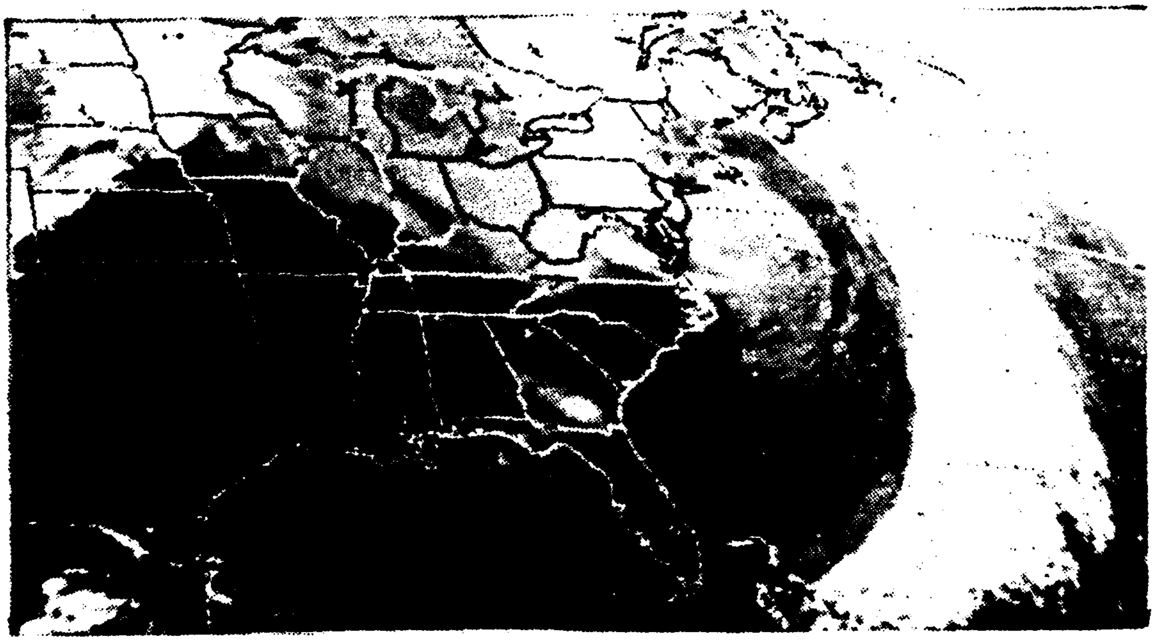

Figure 2.31 GOES infrared satellite image valid 2001 GMT 20 January 1986.

analysis (Fig. 2.33). The model correctly reflected the diffluent structure of the trough. The short-wave trough off the coast of South Carolina was not reflected in the height forecast. However, the forecast 500 mb vorticity field (not shown) does resolve the eastern short-wave trough and indicates PVA over Florida, and the Carolina and Virginia coasts.

The sea-level low pressure center over West Virginia was well forecast (Fig. 2.34). However, the troughing on the Carolina coast is not captured. Instead, the model extends a weak trough southward from South Carolina to western Cuba. Consequently, the model does resolve the southerly flow ahead of the shortwave, but it is weaker than observed with less of an onshore component. The major cold front associated with the western shortwave is well forecast as it crosses the southeastern states. The 6 mb error off the Carolina coast (Fig. 2.35) results from the forecast missing the troughing on the Carolina coast.

The 12 h forecast indicates three areas of intense precipitation (Fig. 2.36): over Ohio; over Virginia; and over the straits of Florida. These areas are in agreement with surface observations and satellite imagery. However, an area of precipitation (the southern extension of the area over Virginia) observed over Georgia and South Carolina was not forecast. The northern forecast precipitation areas are related to the principal cyclone over West Virginia and warm air advection center on the East Coast. The Florida precipitation is driven by weak 500 mb PVA and surface trough off Florida. Most of the predicted precipitation is stratiform with only a small convective component in all three areas.

2. 24 h prognosis VT: 0000 GMT 20 JANUARY 1986

The 24 h forecast correctly captures the strong deepening of the Midwest shortwave (Fig. 2.37). The forecast heights continue to be 60 m higher than the analysis over coastal South Carolina and seaward of the Carolina coast (Fig. 2.38). Over coastal South Carolina the error results from the forecast cut-off 500 mb low being too weak. Seaward of the Carolina coast the NORAPS model did not forecast a significant shortwave. The 500 mb vorticity forecast (not shown) continues to show the eastern short-wave trough as it moves northeastward.

At the surface, an elongated double centered low is forecast rather than the more concentrated analyzed vortex (Fig. 2.39). This elongated low is in close agreement with the NMC analysis (not shown). Troughing forecast along the coast of South Carolina, Georgia and Florida has sharper cyclonic curvature than analyzed. A

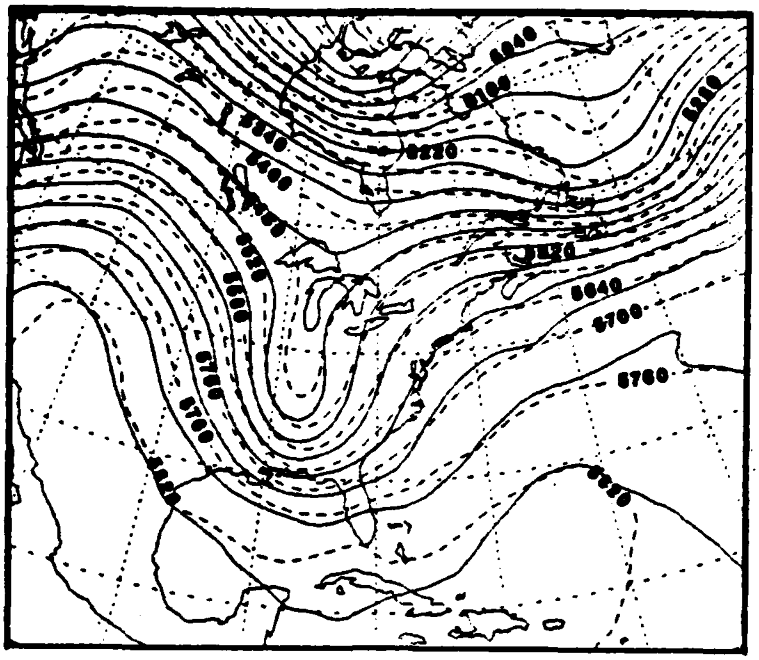

Figure 2.32 12 h 500 mb prognosis and analysis.
Predicted (dashed) and verifying heights (solid) at 500 mb
for 1200 GMT 19 January 1986.

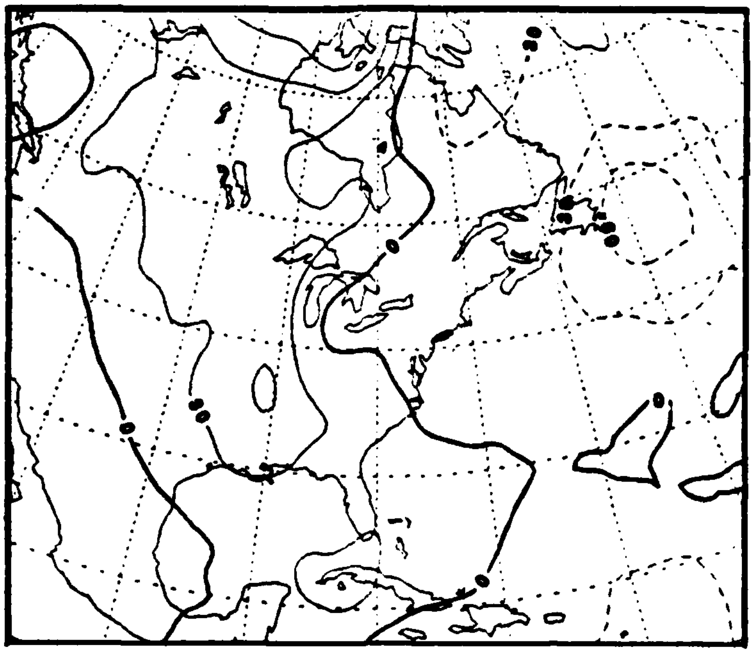

Figure 2.33 Predicted minus analyzed heights (m) at 500 mb.
Positive(negative) values indicate predicted heights are
larger (smaller) than analyzed values at 1200 GMT 19 January 1986.

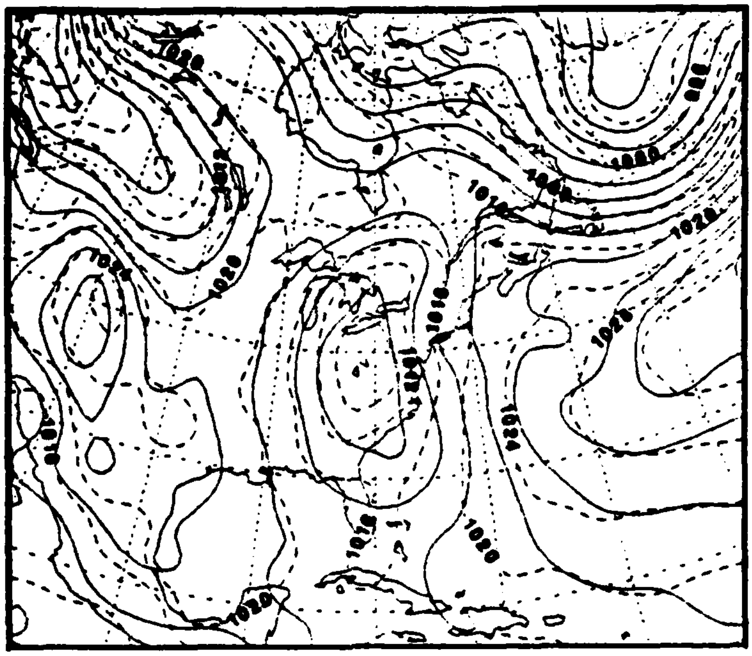

Figure 2.34 12 h sea-level pressure prognosis and analysis. Predicted (dashed) and verifying pressures (solid) at sea-level for 1200 GMT 19 January 1986.

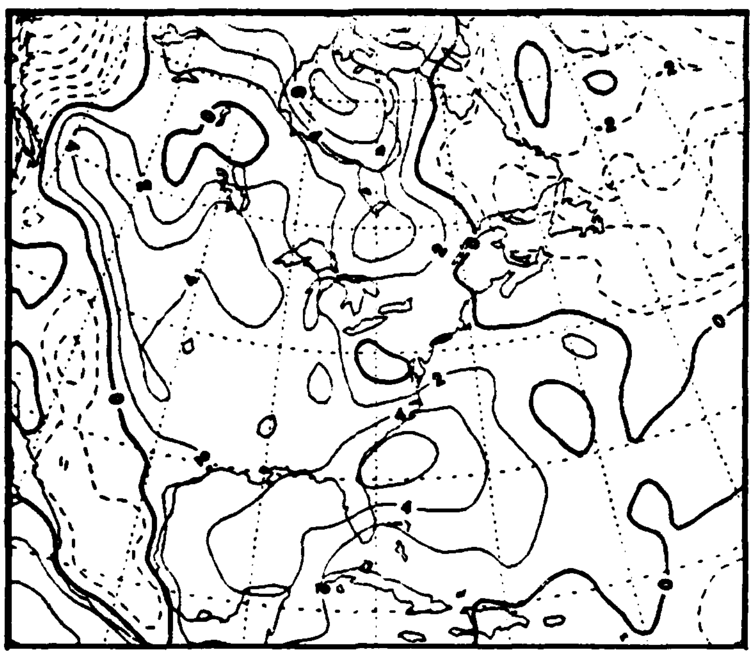

Figure 2.35 Predicted minus analyzed pressure (mb) at sea-level. Positive (negative) values indicate predicted pressures are larger (smaller) than analyzed values at 1200 GMT 19 January 1986.

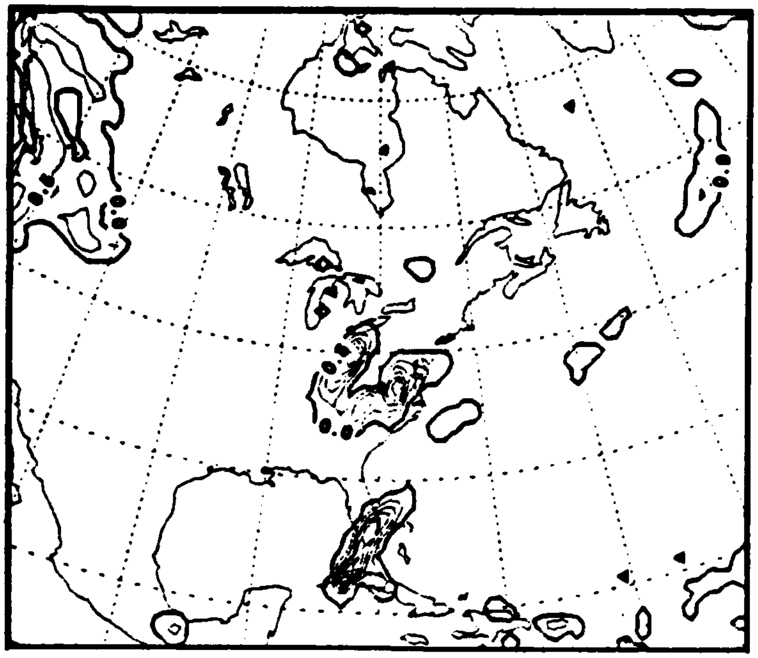

Figure 2.36 12 h forecast of total precipitation (cm) accumulated over the previous 12 h valid 1200 GMT 19 January 1986.

large area of 8 mb error off the coast of New Jersey (Fig. 2.40) is the result of an east-west trough being analyzed over an area where southerly flow had been forecast. The forecast is correct in the general structure of the southerly surface flow; however, the analyzed southerly current is stronger and has more of an onshore component from New Jersey to Massachusetts.

At 24 h, the model forecast has a concentrated band of precipitation (Fig. 2.41) along the East Coast from Cuba to Maine. The forecast precipitation appears to lag the satellite cloud patterns (Fig. 2.15) associated with the major precipitation over the western North Atlantic. This total precipitation forecast is an accumulation over 12 h and would be expected to lag the cloud pattern associated with a moving system.

3. 36 h prognosis VT: 1200 GMT 20 JANUARY 1986

The general aspects of the mature stage of the cyclone were forecast well. The model moved the cut-off 500 mb low eastward as was observed (Fig. 2.42). The forecast position was approximately 3° of latitude southwest of the observed center. The cut-off low was forecast 120 m weaker than observed (Fig. 2.43). At this time, the forecast loses the eastern short-wave trough. A new short-wave trough, which is evident in the analyzed vorticity field (Fig. 2.24), southeast of the 500 mb center also is not resolved by the model.

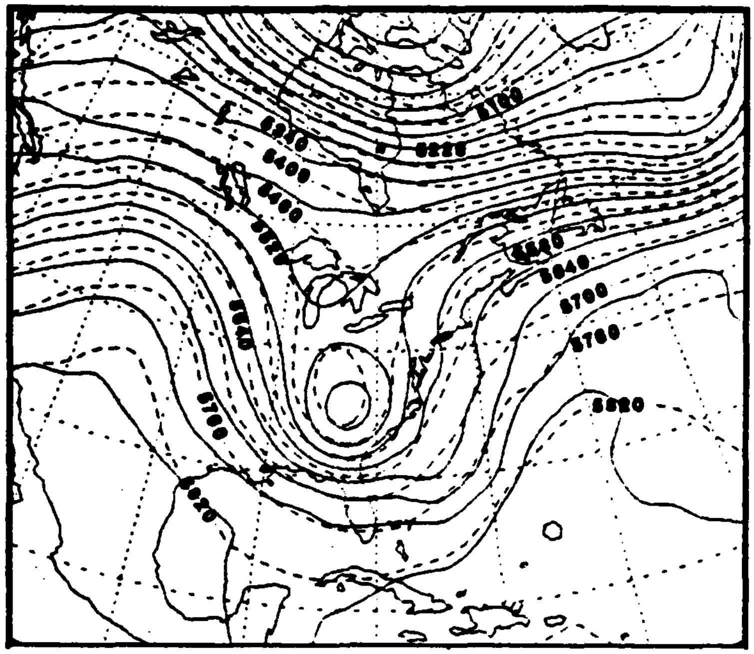

Figure 2.37 24 h 500 mb prognosis and analysis.
Predicted (dashed) and verifying heights (solid) at 500 mb
for 0000 GMT 20 January 1986.

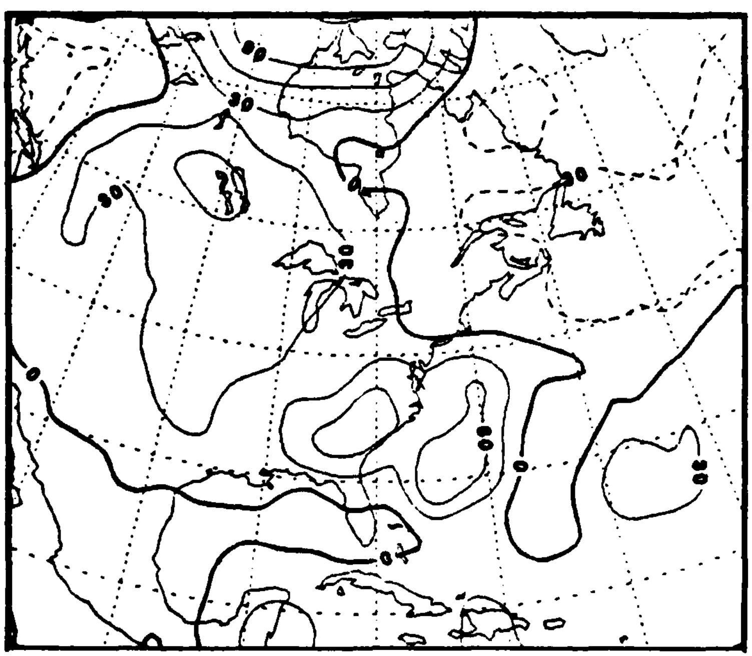

Figure 2.38 Predicted minus analyzed heights (m) at 500 mb.
Positive(negative) values indicate predicted heights are
larger (smaller) than analyzed values at 0000 GMT 20 January 1986.

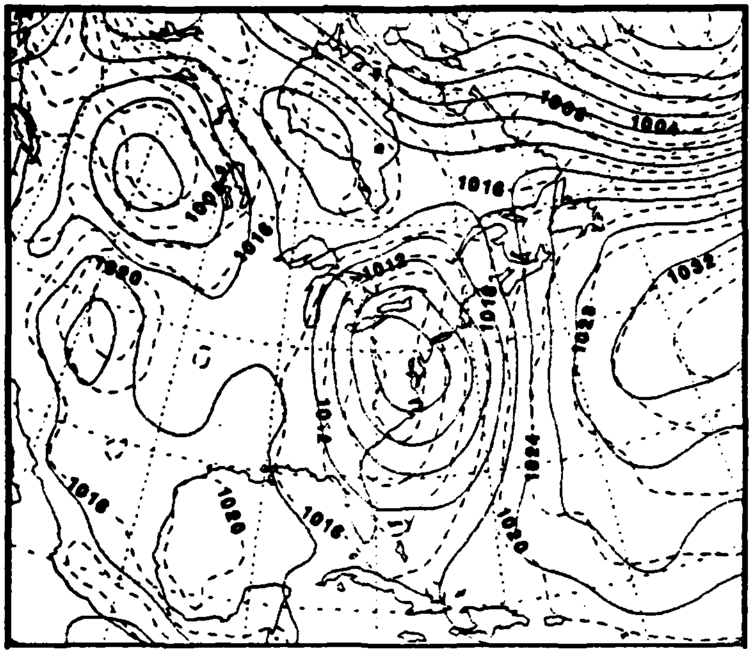

Figure 2.39 24 h sea-level pressure prognosis and analysis. Predicted (dashed) and verifying pressures (solid) at sea-level for 0000 GMT 20 January 1986.

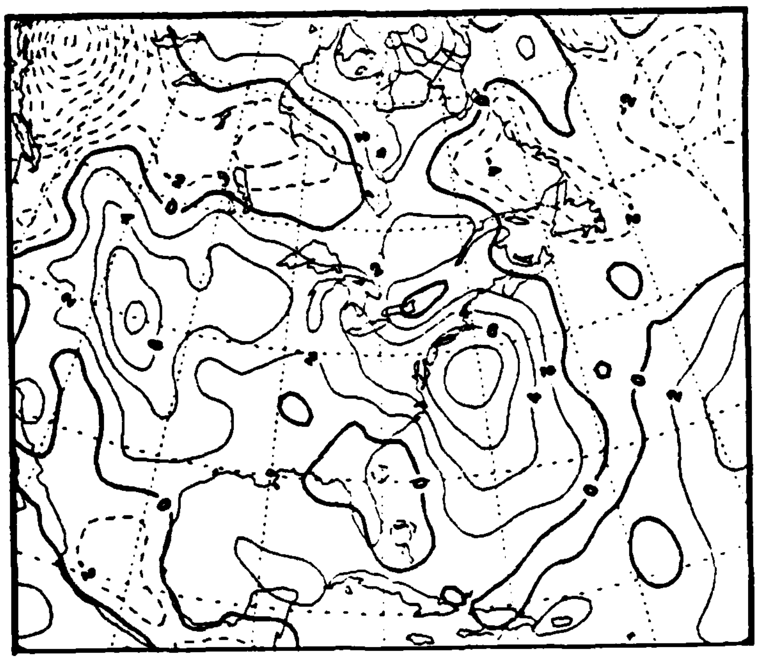

Figure 2.40 Predicted minus analyzed pressure (mb) at sea-level. Positive (negative) values indicate predicted pressures are larger (smaller) than analyzed values at 0000 GMT 20 January 1986.

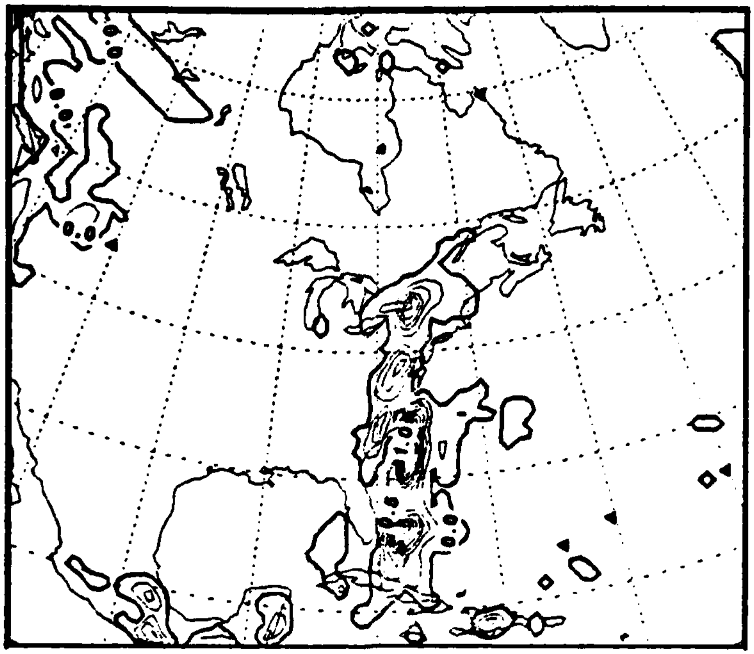

Figure 2.41 24 h forec st of total precipitation (cm) accumulated o er the previous 12 h valid 0000 GMT 20 January 1986.

The sea-level pressure forecast center was 2° of latitude south of the observed center (Fig. 2.44), similar to the 500 mb error. The forecast appears to be slow because it over-emphasized the deepening associated with the amplifying trough over the Carolina coast. The forecast central pressure of 990 mb agreed well with the observed value. However, the forecast low was much more concentric than observed. The 12 mb error over New Brunswick (Fig. 2.45) results from cyclone forecast position errors combined with forecast intensity errors.

The precipitation extent over the northeastern United States and New Brunswick agrees with surface weather reports. The forecast accumulated total precipitation pattern (Fig. 2.46) continues to lag the major organized precipitation cloudiness over the western North Atlantic as expected.

4. 48 h prognosis VT: 0000 GMT 21 JANUARY 1986

The 48 h 500 mb prognosis did not perform as well as the earlier forecasts (Fig. 2.47). While the forecast cut-off low remained relatively stationary between 36h and 48 h, the actual cut-off low was observed to move northeastward. The forecast cut-off low continued to deepen, while the observed low changed little in intensity. This resulted in the forecast low being only 60 m weaker than observed. An error of

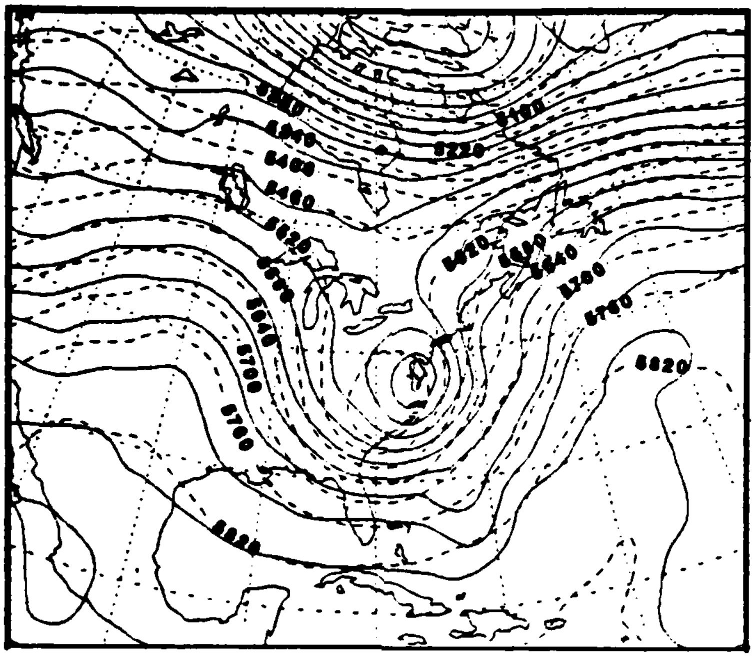

Figure 2.42 36 h 500 mb prognosis and analysis. Predicted (dashed) and verifying heights (solid) at 500 mb for 1200 GMT 20 January 1986.

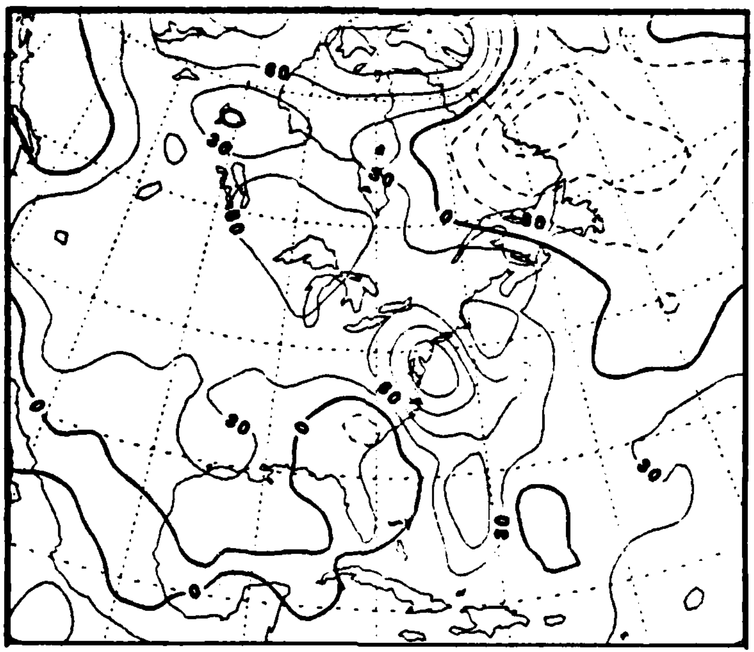

Figure 2.43 Predicted minus analyzed heights (m) at 500 mb. Positive(negative) values indicate predicted heights are larger (smaller) than analyzed values at 1200 GMT 20 January 1986.

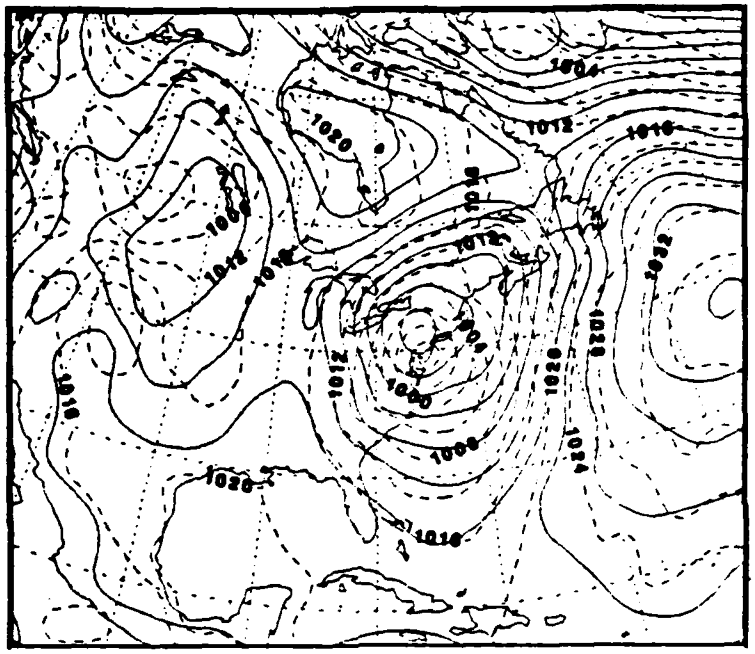

Figure 2.44 36 h sea-level pressure prognosis and analysis. Predicted (dashed) and verifying pressures (solid) at sea-level for 1200 GMT 20 January 1986.

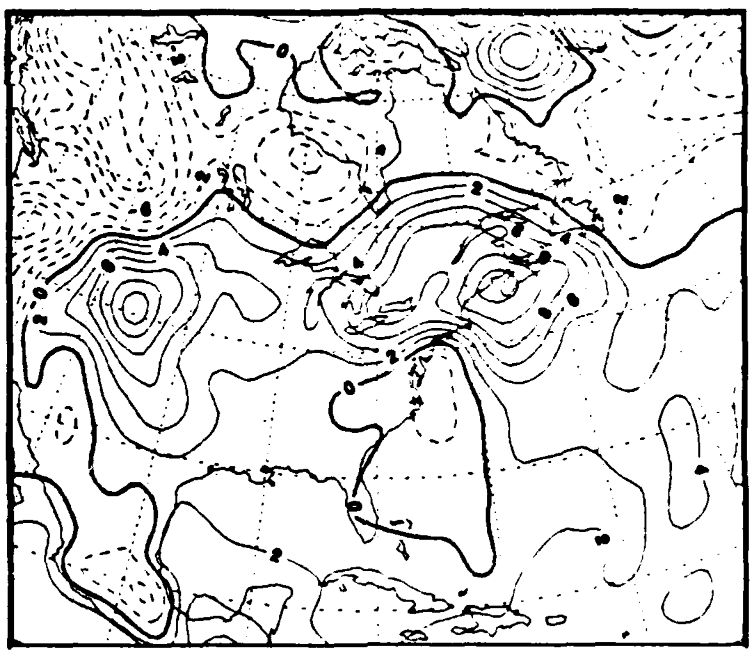

Figure 2.45 Predicted minus analyzed pressure (mb) at sea-level. Positive (negative) values indicate predicted pressures are larger (smaller) than analyzed values at 1200 GMT 20 January 1986.

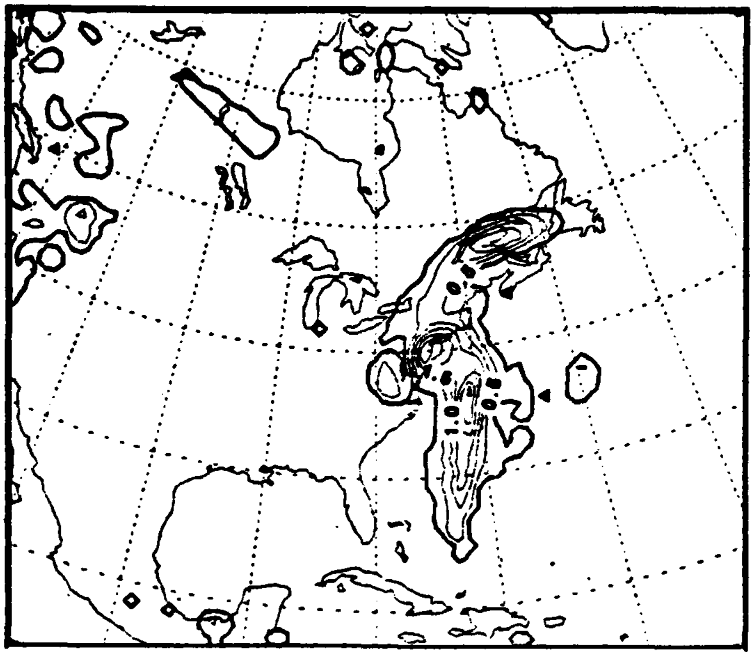

Figure 2.46 36 h forecast of total precipitation (cm) accumulated over the previous 12 h valid 1200 GMT 20 January 1986.

180 m is located off the coast of Massachusetts (Fig. 2.48). Much of this error can be attributed to the center of the closed circulation on the forecast being 3° of latitude south of the observed circulation center. However, the forecast trough also had a greater amplitude. The slow movement and continued development in the forecast may be the result of stronger warm advection forecast into New England than was observed. The observed warm advection at 36 h is farther east into Nova Scotia.

The forecast sea-level pressure center also is erroneously forecast 4° of latitude too far to the southwest (Fig. 2.49). This agrees with the errors found in the upper-level forecast fields. The 48 h sea-level pressure prognosis shows significant errors in the position of frontal troughs. The 10 mb errors over New Brunswick (Fig. 2.50) result from the forecast being slow on the movement of the cyclone, and not filling the cyclone as rapidly as was observed.

The location and extent of precipitation in the 48 h precipitation forecast was in remarkable agreement with surface weather reports over New England and the Maritime Provinces. The precipitation forecast no longer lags the organized precipitation cloudiness between 60°W and 70°W (Fig. 2.51). The dry slot of the mature cyclone over coastal New England observed in the satellite images is also well

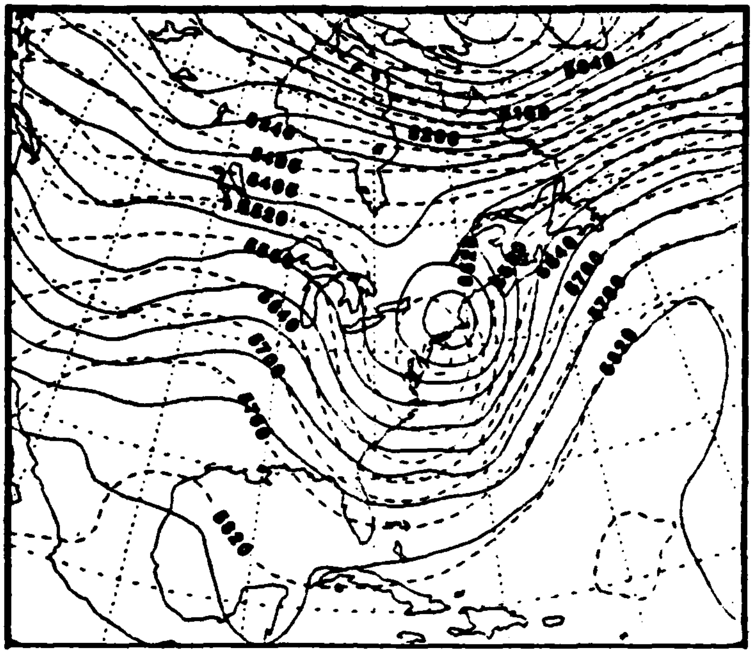

Figure 2.47 48 h 500 mb prognosis and analysis. Predicted (dashed) and verifying heights (solid) at 500 mb for 0000 GMT 21 January 1986.

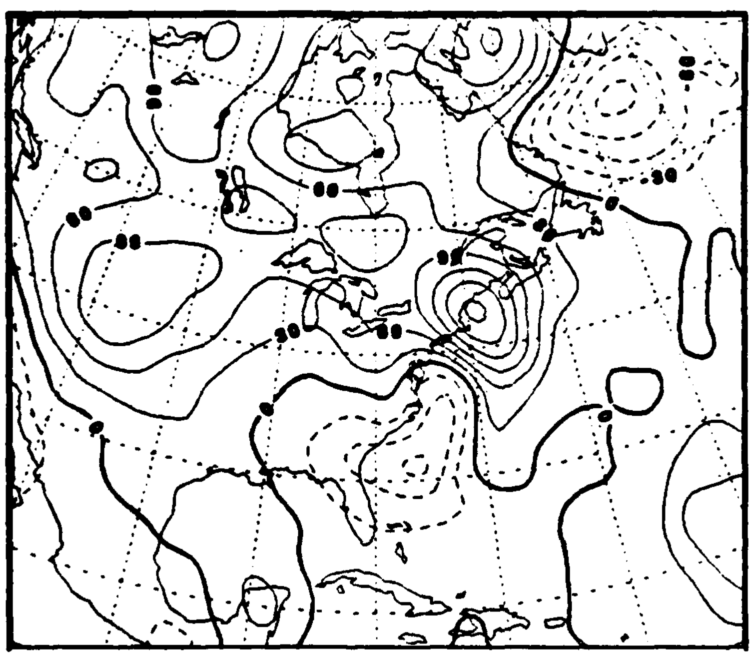

Figure 2.48 Predicted minus analyzed heights (m) at 500 mb. Positive(negative) values indicate predicted heights are larger (smaller) than analyzed values at 0000 GMT 21 January 1986.

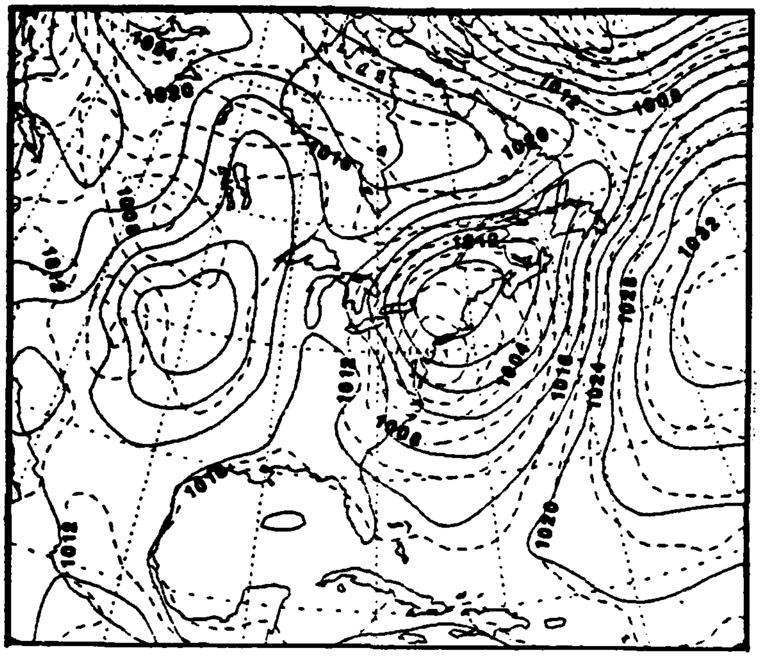

Figure 2.49 48 h sea-level pressure prognosis and analysis. Predicted (dashed) and verifying pressures (solid) at sea-level for 0000 GMT 21 January 1986.

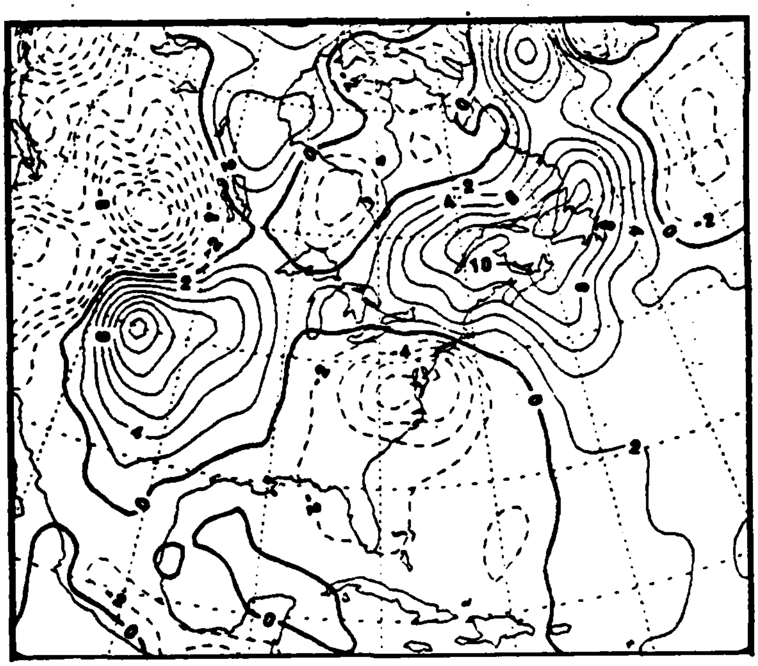

Figure 2.50 Predicted minus analyzed pressure (mb) at sea-level. Positive (negative) values indicate predicted pressures are larger (smaller) than analyzed values at 0000 GMT 21 January 1986.

represented in the prec.p.tation forecast. The boundary of the dry slot visible in the GOES IR imagery at 2001 GMT 20 January 1986 (Fig. 2.29) corresponds closely to the boundary of no precipitation in the 48 h forecast.

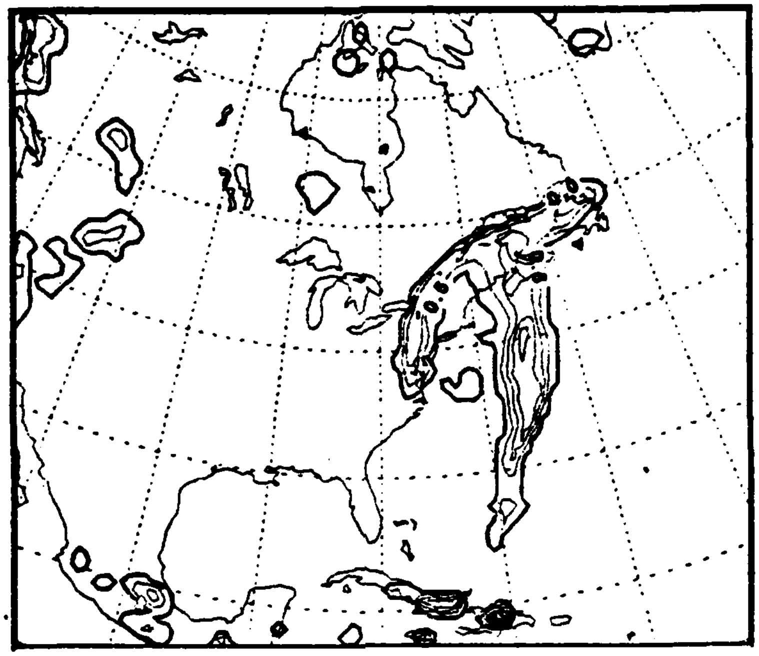

Figure 2.51 48 h forecast of total precipitation (cm) accumulated over the previous 12 h valid 0000 GMT 21 January 1986.

5. **Summary of NORAPS verification for IOP 1**

Overall, the NORAPS forecast of the synoptic-scale features was successful. The intensification of the second 500 mb trough and associated sea-level cyclogenesis were well forecast. While NORAPS forecast significant development of the 500 mb shortwave and cut-off low formation, the full extent of this 500 mb development was underforecast. The predicted 500 mb cut-off center is 90 m too weak at 36 h and 120 m too weak at 48 h. However, the forecast intensity of surface cyclogenesis agrees closely with analyses (Fig. 2.52).

NORAPS precipitation forecasts were surprisingly good. The significant upward vertical motion area associated with the eastern shortwave was captured by the model. The accumulated precipitation forecast agrees well with surface observations over land and satellite cloud imagery over the oceans.

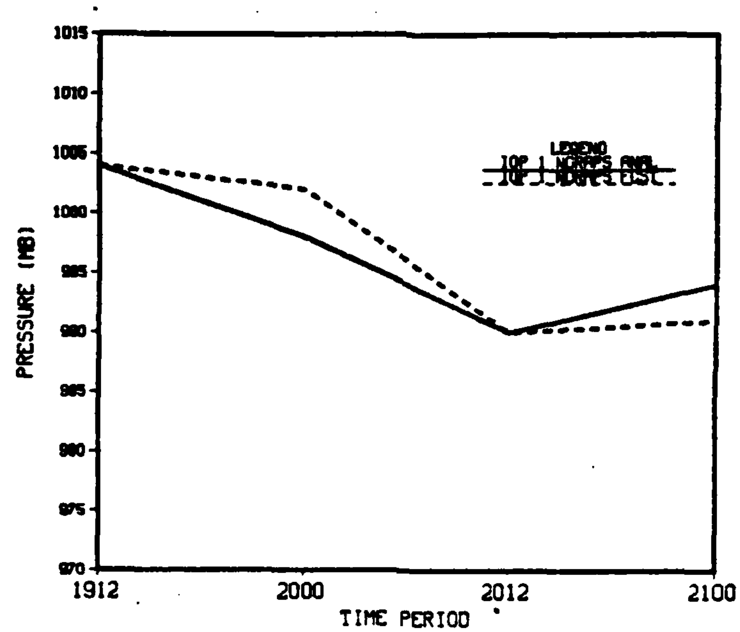

Figure 2.52 Forecast (dashed) and analyzed (solid) pressure for IOP 1 cyclones between 1200 GMT 18 and 0000 GMT 21 January.

Major errors in the NORAPS forecast were in the sub-synoptic details of the forecast. The 24 h NORAPS forecast describes two widely separated sea-level low pressure centers at 0000 GMT 20 January, while the NORAPS analysis describes one center (Fig. 2.53). However, the double centered low forecast by NORAPS at 24 h is reflected in the corresponding NMC sea-level pressure analysis (not shown). After 24 h the NORAPS forecast preferentially deepens the southern surface center, resulting in a forecast surface system that verifies too far south and west (Fig. 2.53). The strong troughing over New England and significant warm advection maximum are not forecast.

H. SUMMARY OF IOP 1 CYCLOGENESIS

IOP 1 was dominated by the existence of two significant 500 mb short-wave troughs. The first trough moved from the Gulf Coast northeastward to New England. Moderate PVA over the eastern Gulf Coast and Georgia associated with the first shortwave, and upward vertical motions associated with an intensifying STJ streak across northern Florida contributed to enhanced frontal type cloudiness off the Carolina coast early in IOP 1.

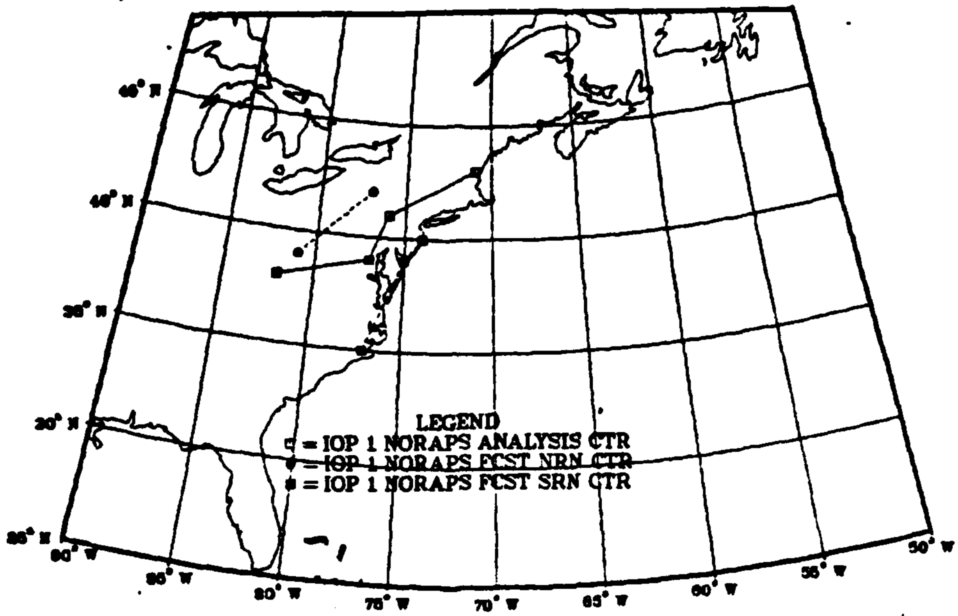

Figure 2.53 Forecast (dashed) and analyzed (solid) positions for IOP 1 cyclones between 1200 GMT 18 and 0000 GMT 21 January 1986.

As IOP 1 progressed, the first 500 mb shortwave was reflected at the surface as a trough extending from Kentucky over the Carolina coast. The southerly flow east of this trough increased the low-level warm advection, baroclinity and moisture gradient along the East Coast.

The second upper-level short-wave trough over the Mississippi Valley moved southeastward and overtook the first trough over western North Carolina in the middle of IOP 1. A strong but relatively dry cold front swept eastward in advance of the second short-wave trough. Low-level cold advection and strong PVA in advance of the second shortwave produced significant 500 mb height falls and a cut-off 500 mb vortex over western North Carolina.

Strong cyclogenesis expected as the surface cyclone associated with the strong 500 mb shortwave and upper front approached the Carolina coast did not occur. One probable explanation is that differential PVA and low-level warm advection occurred in different areas. Near the middle of IOP 1 the upper-level PVA was over North Carolina and Virginia, while the strong low-level warm advection was farther north over New York and Pennsylvania. This resulted in an oval shaped sea-level low pressure center extending from the Virginia Capes to Lake Erie.

In summary, the two short-wave trough systems of IOP 1 interacted in a manner that decreased the rate of surface cyclogenesis associated with the second system. The first shortwave initiated a surface trough over the Carolina coast. This surface trough significantly altered the warm air advection in advance of the second system. When the second system arrived at the coast, the low-level warm air advection pattern of the first trough had already organized the isotherms parallel to the flow in advance of the second system. Therefore, the significant warm advection was not east or northeast of the surface low, but north of the low. Because the area of PVA was separated from the area of low-level warm advection, the vertical motions associated with PVA and low-level warm advection did not reinforce each other sufficiently for rapid cyclogenesis.

The synoptic scale NORAPS forecasts are reasonably accurate. The precipitation patterns associated with the eastern shortwave are well captured. However, there were problems resolving the mesoscale structure as the second short-wave trough merged with the eastern system. For example, the eastern short-wave trough disappeared completely from the height forecast after the middle of IOP 1, and too much surface cyclogenesis was forecast for the southern low pressure center.

I. FUTURE RESEARCH OPPORTUNITIES

The first 500 mb shortwave was well observed during early periods of IOP 1 by the CLASS network. Aircraft flights investigated temperature and moisture profiles east of the Carolina coast in advance of the first shortwave. This aircraft data can be used to define the boundary layer structure of the southerly maritime flow into the system. The high temporal and spatial resolution of the CLASS soundings will allow construction of cross-sections through the system early in IOP 1. Most research is concentrated on intense cyclogenetic events. IOP 1 presents an opportunity to investigate a more modest, yet important, system.

The Midwest trough developed into a cut-off 500 mb vortex passing through the 3-h sounding network. These 3-h rawinsondes will provide higher time resolution data to study upper tropospheric cyclogenesis and formation of an upper front. Previous studies were limited to 12-h temporal resolution. Data from the Sabreliner mission flown in the vicinity of the upper closed circulation can be used to document the presence and define the structure of the upper front and cold-dome.

This synoptic study indicated that the strong upper short-wave trough associated with IOP 1 cyclogenesis did not couple strongly with the lower troposphere. It is important to determine why this coupling was so weak. Diagnostic analyses of the Pettersen development equation or the quasi-geostrophic omega equation from the GALE objective analyses would quantify the relative contributions of upper tropospheric and low tropospheric circulations for this case. Even though this was a modest, not intense, cyclogenesis case, much insight can be gained through additional studies of this IOP.

III. SYNOPTIC DISCUSSION OF IOP 9

IOP 9 was selected for investigation based upon the explosive cyclogenesis that occurred between 0000 GMT 25 and 0000 GMT 26 February 1986. The cyclone of IOP 9, which subsequently deepened 27 mb in 24 h, was located over the Midwest at the beginning of the IOP. This cyclone was associated with an amplifying short-wave trough in the cold air following a major frontal passage. A second cyclone also developed as a frontal wave in an area of weak pressure gradient off the Carolina coast.

A. 1200 GMT 24 FEBRUARY 1986

During IOP 9, the long-wave pattern over the United States consisted of a ridge over the western U.S. and a trough over the eastern U.S. (Fig. 3.1). The 500 mb analysis reveals a significant short-wave trough in the northwesterly flow west of the long-wave trough axis. This 500 mb short-wave trough axis extends from Lake Michigan southward through Mississippi. An area of strong positive vorticity ($+22 \times 10^{-5} s^{-1}$) is associated with this 500 mb shortwave. The NORAPS 500 mb height and vorticity analysis suggests weak short-wave activity east of the Atlantic coast, although these features are disorganized.

The NORAPS sea-level pressure analysis indicates a wave over eastern Kentucky associated with the first trough (Fig. 3.2). The 1000-500 mb thickness analysis indicates that the frontal wave lies in a well-defined polar frontal zone that extends from the central U.S. eastward into the western North Atlantic. The cold front associated with the frontal wave extends southwestward across northern Louisiana into east Texas. Shallow cold air damming east of the Appalachian Mountains extends from Pennsylvania to North Carolina.

The western North Atlantic Ocean is dominated by troughing and an associated front extends from a 998 mb low pressure center off Nova Scotia at 47°N, 54°W, through a secondary 1007 mb center at 38°N, 56°W to the Florida Straits. The 1020 mb North Atlantic anticyclone is much weaker and farther south (center south of 30°N) than in IOP 1.

The Midwest short-wave trough is more pronounced at 250 mb than at 500 mb (Figs. 3.3 and 3.1). The 250 mb isotachs (Fig. 3.3) indicate a strong polar jet streak

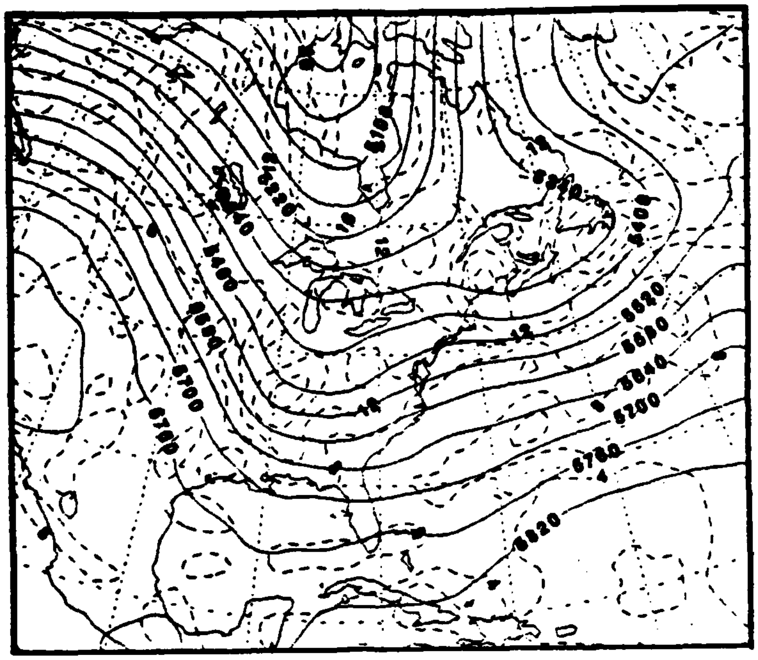

Figure 3.1 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) 10^{-5} s^{-1} valid 1200 GMT 24 February 1986.

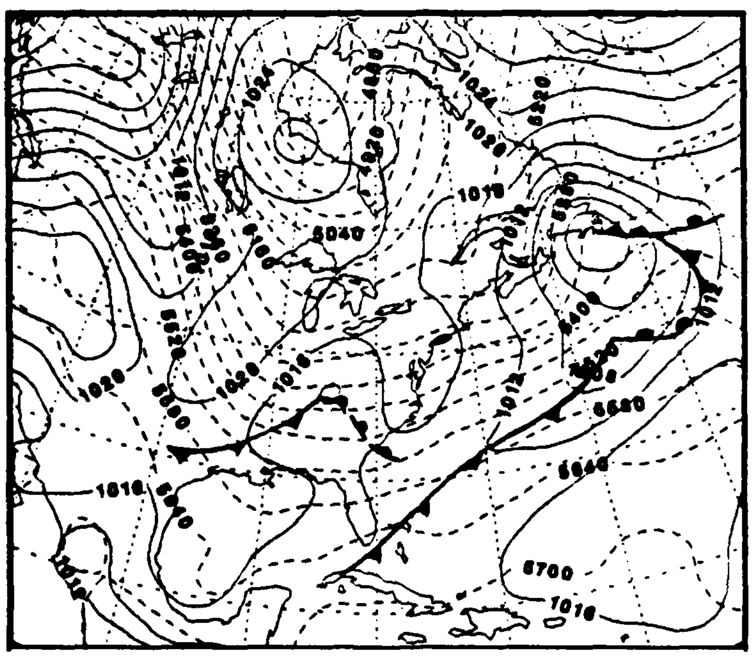

Figure 3.2 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 1200 GMT 24 February 1986.

upstream of the trough with a 60 m s^{-1} jet maximum. A noteworthy subtropical jet streak extends over the cold front from the Gulf of Mexico northeastward into the North Atlantic Ocean. An 80 m s^{-1} isotach maximum is analyzed east of northern Florida at 30°N, 80°W. This feature in the upper air isotach analysis is supported by a rawinsonde over the Bahamas and two aireps in the vicinity of 27°N, 73°W.

The GOES visual imagery at 1531 GMT (Fig. 3.4) indicates a well-organized, cyclonically-curved, cloud band from southeastern Kentucky to central Alabama associated with the frontal wave over eastern Kentucky. The cloud band has a lumpy texture indicating convection, with the strongest convective activity centered over southeastern Kentucky. No frontal cloudiness is observed west of Alabama. However, considerable low overcast covers the Ohio River Valley. Off the East Coast, several broad northwest-southeast oriented lines of cellular clouds are present behind the tail of the previous cold front. Significant features of interest are two small areas of enhanced cloudiness in the tail of the cold frontal band. The first consists of a convective cloud mass with limited cirrus blow-off at 27°N, 76°W over the northernmost Bahamas, while the second center with more pronounced blow-off is located east-northeast of the first at 28°N, 73.5°W. Earlier GOES visual imagery at 1231 GMT (not shown) indicates extensive low cloudiness over Florida, coastal Georgia, and North and South Carolina, which agrees with the fog reports over Florida and coastal Georgia on the 1200 GMT NMC sea-level pressure analysis. The 1200 GMT surface observations also indicate rain and rainshowers reported in association with the cold front in the central United States. Shallow fog is reported from immediately behind the front to central Illinois and Missouri. Snow was reported over Ohio, Indiana and northern Illinois. Shallow and patchy fog were reported over most of the area influenced by cold air damming including Maryland, Virginia, North and South Carolina.

The GOES water vapor imagery at 1131 GMT (not shown) indicates a relatively dry pool of mid-tropospheric air that is associated with the short-wave trough over Wisconsin, Illinois and Indiana. The GOES water vapor imagery also clearly indicates a dry slot associated with a branch of the subtropical jet that extends across northern Mexico, central Florida and then northeastward into the North Atlantic Ocean. This dry slot occurs on the cyclonic side of the subtropical jet streak and corresponds closely to the jet streak axis (Fig. 3.3).

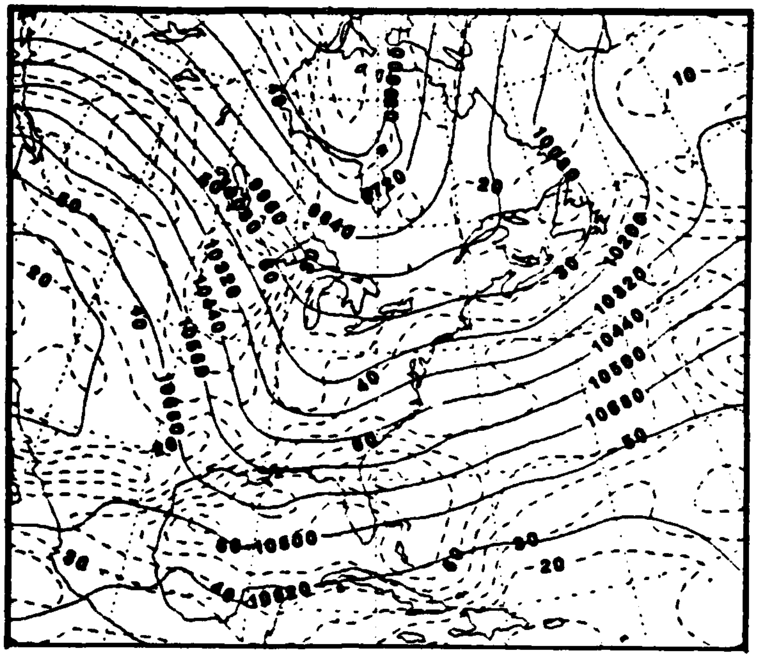

Figure 3.3 250 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 250 mb valid 1200 GMT 24 February 1986.

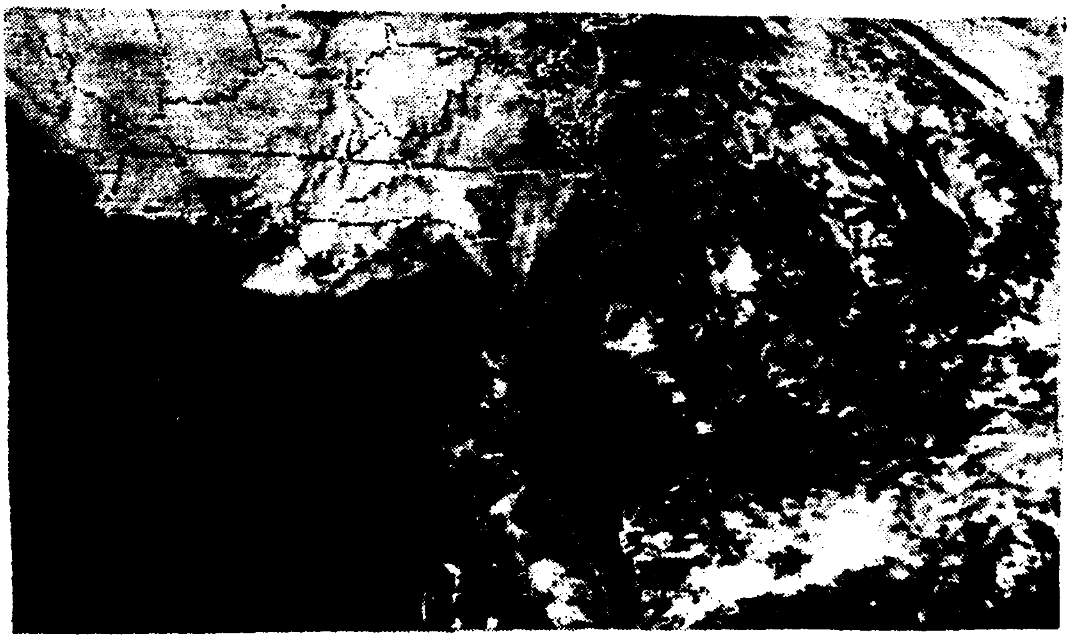

Figure 3.4 GOES visible satellite image valid 1531 GMT 24 February 1986.

B. 0000 GMT 25 FEBRUARY 1986

During the first synoptic period of IOP 9, the 500 mb short-wave trough that extended from the Carolinas southward across Florida was moving eastward (Fig. 3.5). An area of strong positive absolute vorticity ($+20 \times 10^{-5} s^{-1}$) is located downstream of the 500 mb trough over coastal North Carolina and extends southeastward toward 30°N, 75°W. This vorticity maximum and strong 500 mb flow produces strong PVA off the Carolina Coast.

The sea-level pressure analysis shows the 1009 mb low over eastern Kentucky has moved over the coast of South Carolina and deepened to 1007 mb (Fig. 3.6). The associated cold front is analyzed across southern Georgia and along the Gulf Coast to Corpus Christi Texas. The GOES visual imagery at 1831 GMT six hours prior to the analysis time (Fig. 3.7), indicates a well-organized, cyclonically-curved band of clouds from North Carolina southwestward across western South Carolina and central Georgia that is associated with this cold front. Cold air damming east of the Applalachian Mountains has been replaced by a trough that extends northward from the surface low over coastal South Carolina.

To the east, a surface wave with a 1006 mb central pressure has formed from the small areas of enhanced cloudiness in the tail of the cold frontal band at the previous synoptic time. The GOES visual imagery at 1831 GMT (Fig. 3.7) clearly indicates enhancement and broadening of the cloud band east of the Bahamas associated with formation of a surface wave on the front. The GOES 0031 GMT IR satellite imagery (not shown) indicates rapid northeastward movement of the developing wave to approximately 32°N, 67°W. The position of this wave inferred from the satellite imagery does not agree with the NORAPS sea-level pressure analysis (Fig. 3.6) or the NMC final sea-level pressure analysis (not shown), which both indicate a position farther west. The cold front associated with the new wave extends southwestward across western Cuba. The North Atlantic anticyclone remains weak and is displaced well to the southeast.

The 250 mb isotachs (Fig. 3.8) continue to show a strong (70 m s^{-1}), well organized, polar jetstream west of the longwave axis. A more organized subtropical jet streak is evident east of Florida. The 250 mb isotachs have a 70 m s^{-1} jet maximum located near the Bahamas with a 60 m s^{-1} isotach from central Florida eastward to 32°N, 70°W. The frontal wave growth at the surface corresponds closely to the subtropical jet streak entrance region (Fig. 3.8).

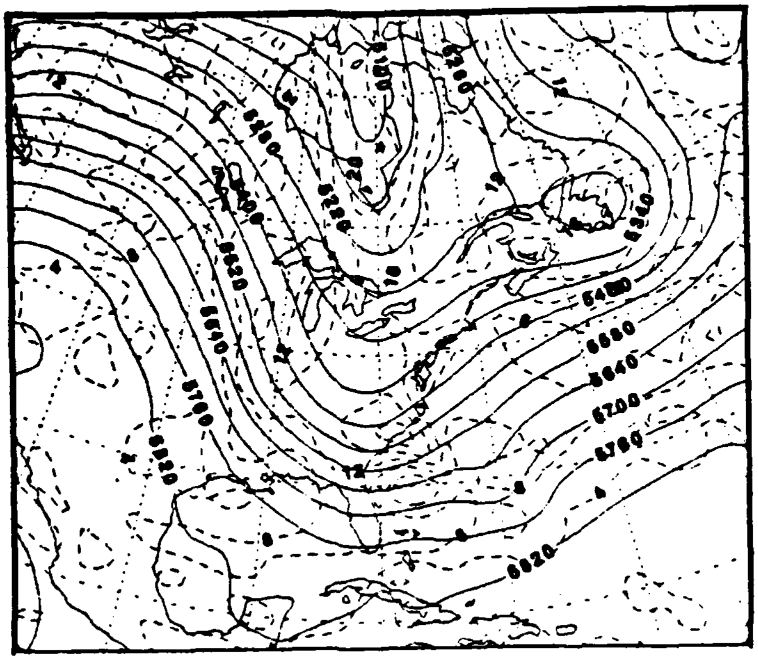

Figure 3.5 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) $10^{-5}\,s^{-1}$ valid 0000 GMT 25 February 1986.

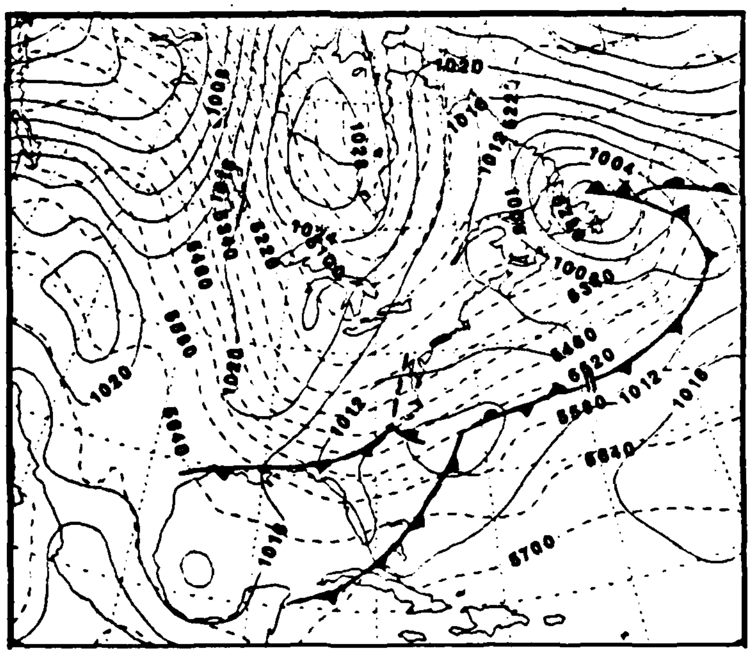

Figure 3.6 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 0000 GMT 25 February 1986.

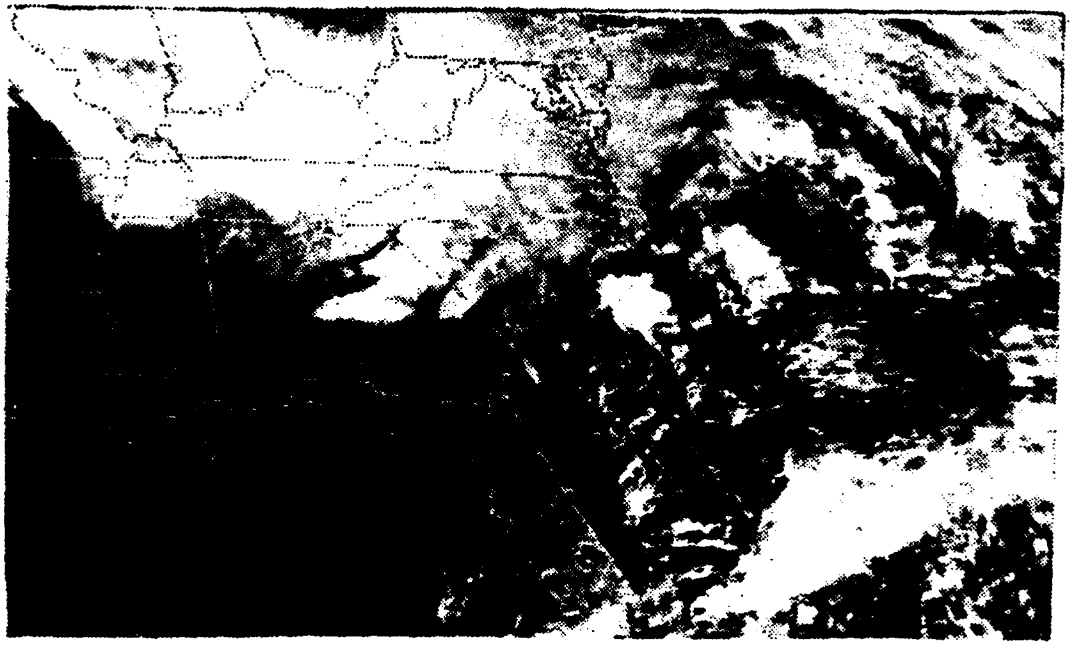

Figure 3.7 GOES visible satellite image valid 1831 GMT 24 February 1986.

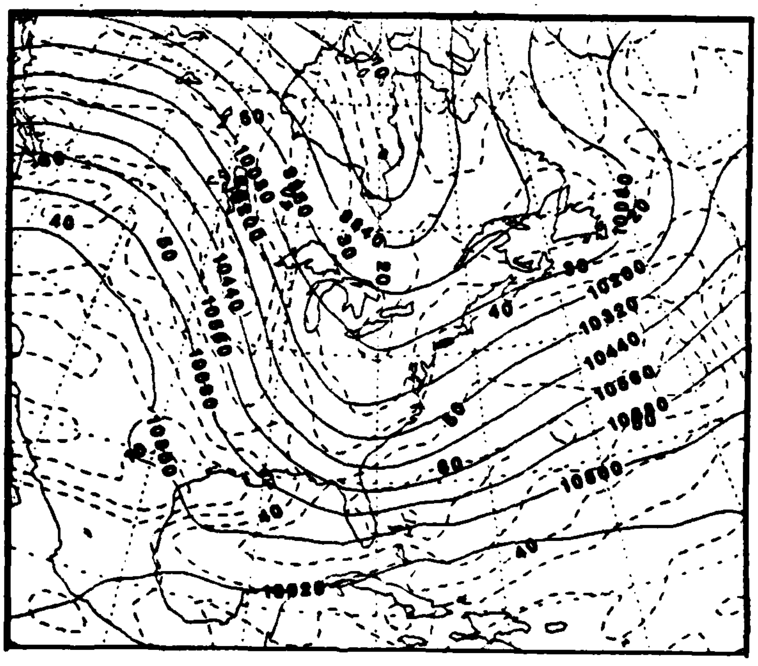

Figure 3.8 250 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 250 mb valid 0000 GMT 25 February 1986.

Four GALE aircraft flights are available to supplement the 0000 GMT observations (GALE, 1986). The King Air investigated pre-storm boundary layer structure in the vicinity of the Gulf Stream between 1846 GMT 24 February and 0052 GMT 25 February. Lightning and heavy showers were observed in the vicinity of 32.5°N, 76.5°W. This corresponds to a thin rope of convective activity within the western-most northwest-southeast oriented line of cellular clouds visible in the GOES visual sector at 1831 GMT 24 February (Fig. 3.7).

The NOAA P3 flight plan included a study of the kinematics and microphysics of rainbands in conjunction with the SPANDAR Doppler radar and the NASA ER2 between 2212 GMT 24 February and 0630 GMT 25 February. Weak cold frontal precipitation, deep at first, becoming shallower and dying throughout the mission were observed. The flight notes concluded that the "cold front" was an inverted trough or coastal front northeast of the frontal wave, which may have contributed to rapid cyclogenesis.

The C-131 conducted airborne and radar coordinated measurements in rainbands between 2306 GMT 24 February and 0627 GMT 25 February. The aircraft track was concentrated in the area over Cape Hatteras and New Bern, North Carolina. The aircraft passed through a band of cells about 20 n mi east of Raleigh-Durham, after which it was clear of the clouds to the coast. The GOES IR sector at 0031 GMT (not shown) indicates the front is past Raleigh. Therefore, the line of cells observed by the C-131 correspond to the cold front associated with the short-wave system.

The Citation flew a dropsonde mission (no winds) between 2130 GMT 24 February and 0800 GMT 25 February. The aircraft flight track provided a good matrix of observations along the coast of Georgia and the Carolinas and out to 150 n mi from the coast. A total of fifteen drops were made during this mission. These drops were made directly between the newly formed wave and the cold front over the Carolina coast (Fig. 3.9). These data can be used to investigate atmospheric conditions over the ocean before the first cyclone over the Carolina coast starts deepening explosively.

C. 1200 GMT 25 FEBRUARY 1986

During the second synoptic period of IOP 9, the shortwave continued to move eastward off the Carolina coast and deepened 60 m (Fig. 3.10). The vorticity maximum ($+16 \times 10^{-5} s^{-1}$) over the Carolina coast moved eastward to 35°N, 70°W.

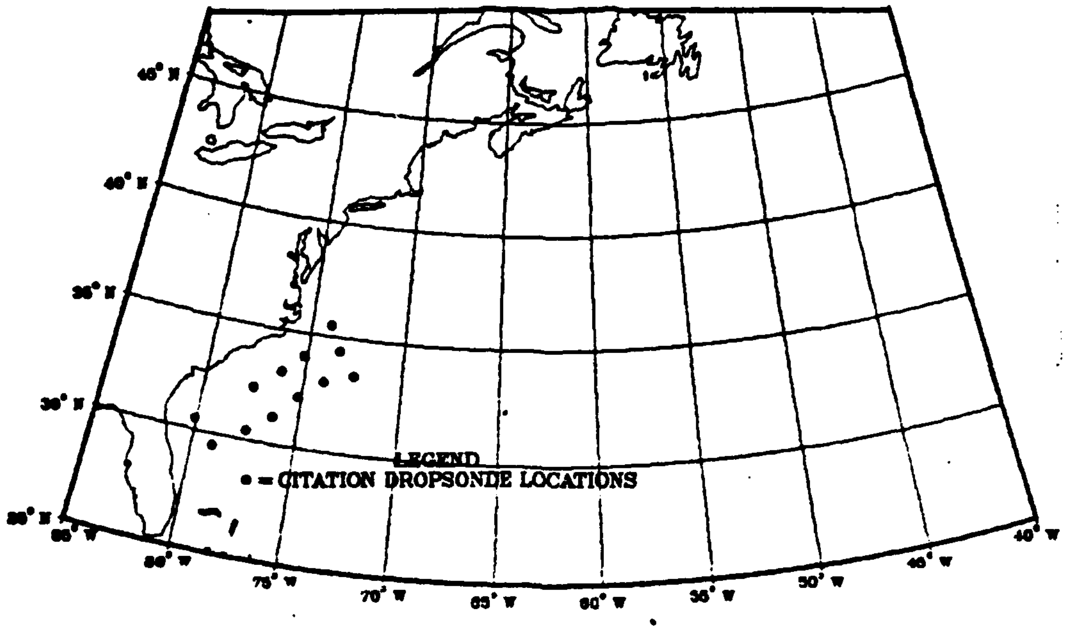

Figure 3.9 Location of Citation dropwindsonde observations between 2130 GMT 24 February and 0800 GMT 25 February 1986 in support of GALE.

The NMC 500 mb height analysis (not shown) disagrees with the NORAPS short-wave trough position. The NMC analysis places the trough farther to the east at 77°W. The NORAPS vorticity analysis is disorganized in the southern part of the trough.

The NORAPS sea-level pressure analysis indicates that the two surface systems have merged into a double-centered low pressure complex off the coast of North Carolina (Fig. 3.11). The more detailed NMC final analysis (not shown) still indicates two distinct centers. The easternmost center (second cyclone at 998 mb) at 34°N, 63°W is associated with the previous frontal wave development. Although the associated front has remained relatively stationary during the past 12 h, the second cyclone has propagated rapidly northeastward along the front.

The western-most center (first cyclone) on the NMC analysis has a central pressure of 990 mb and is analyzed at 35°N, 67°W. It is associated with the shortwave and cyclone over South Carolina 12 h earlier. The cold front associated with this cyclone, which is analyzed as roughly paralleling the cold front of the second cyclone, extends southwestward across Lake Okeechobee and into the Gulf of Mexico. The 1000-500 mb thickness analysis and sea-level pressure analysis (Fig. 3.11) indicate a strong cold air advection pattern behind this cold front.

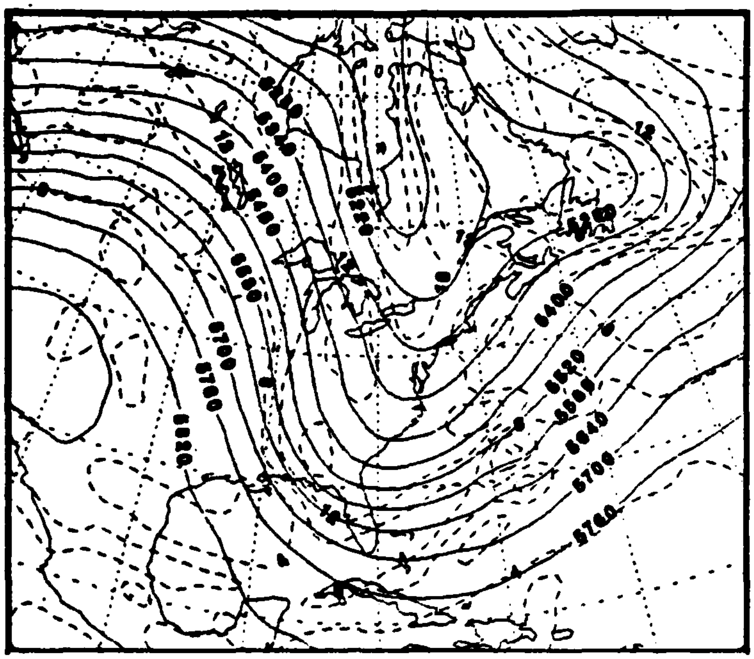

Figure 3.10 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) $10^{-5}\,s^{-1}$ valid 1200 GMT 25 February 1986.

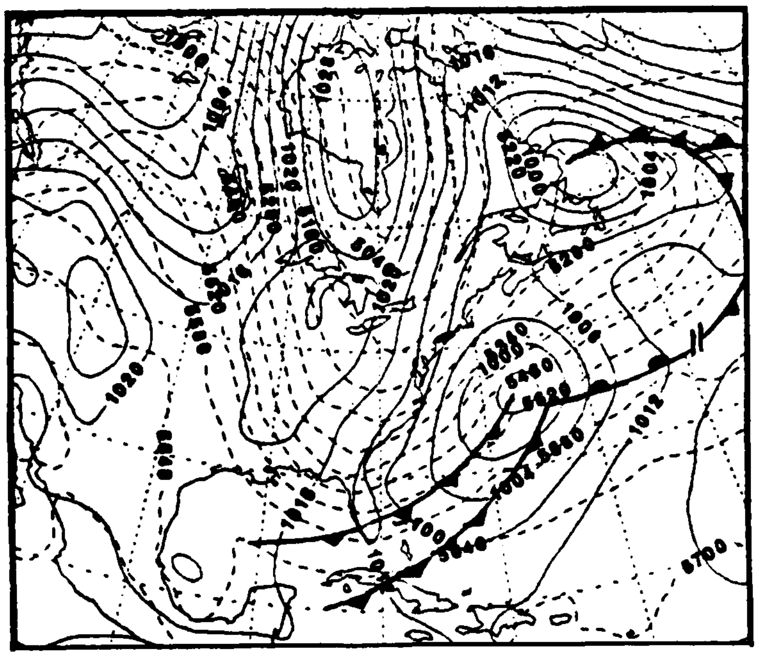

Figure 3.11 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 1200 GMT 25 February 1986.

The NORAPS sea-level pressure analysis mainly describes the western center (first cyclone) with no indication of the eastern frontal wave. The central pressure in the NORAPS analysis is approximately 994 mb, which is 4 mb higher than the NMC hand analysis. The rapid deepening of the first cyclone (1007 to 990 mb in 12 h) has radically altered the sea-level pressure patterns. While the second cyclone had been stronger 12 h earlier, the first cyclone now dominates the sea-level pressure pattern.

The 250 mb isotachs have a broad 50 m s^{-1} jet maximum related to a branch of the subtropical jetstream (Fig. 3.12). This maximum is located in the southwesterly flow east of the trough from Cuba into the central North Atlantic Ocean. The analysis indicates one small 60 m s^{-1} jet streak near the frontal wave location and another over the Bahamas. This analysis benefits from eight aircraft reports along the jet axis. The combination of a jet maximum superposed over 500 mb PVA is conducive to continued deepening of the maritime cyclones.

The GOES visible sector from 1231 GMT (Fig. 3.13) indicates several cyclonic circulations over the North Atlantic Ocean. The cloud signature of the explosively developing first cyclone is the comma-shaped pattern with a surface center at approximately 35°N, 67°W. Considerable anticyclonic curvature is present in the upper cloud patterns north of the low, and an incipient dry tongue is present to the east of the surface position. Typical frontal cloud band broadening associated with the second cyclone is located along 60°W between 33°N and 37°N. The satellite image indicates a distinct separation between the two cyclone centers.

A third vortex signature is also present in the 1231 GMT satellite imagery with a distinct comma cloud near 34°N, 75°W. This system developed from a new convective area southwest of the explosively deepening cyclone during the past 8 h. There is no surface center associated with this system and it is possibly related to another short-wave trough feature at 500 mb. The NORAPS analysis does not resolve this feature.

Two GALE aircraft flights are available to supplement the 1200 GMT observations (GALE, 1986). The Citation flew a dropsonde mission (no winds) between 0820 GMT to 1730 GMT 25 February. The aircraft flight track provided a good matrix of observations along the Carolina coast and Virginia Capes and out to 150 n mi. A total of 14 drops were made behind the analyzed position of the western-most cold front (Fig. 3.14), which should provide good definition of the middle and lower tropospheric conditions behind the front, and in the vicinity of the newly developed comma cloud near 34°N, 75°W.

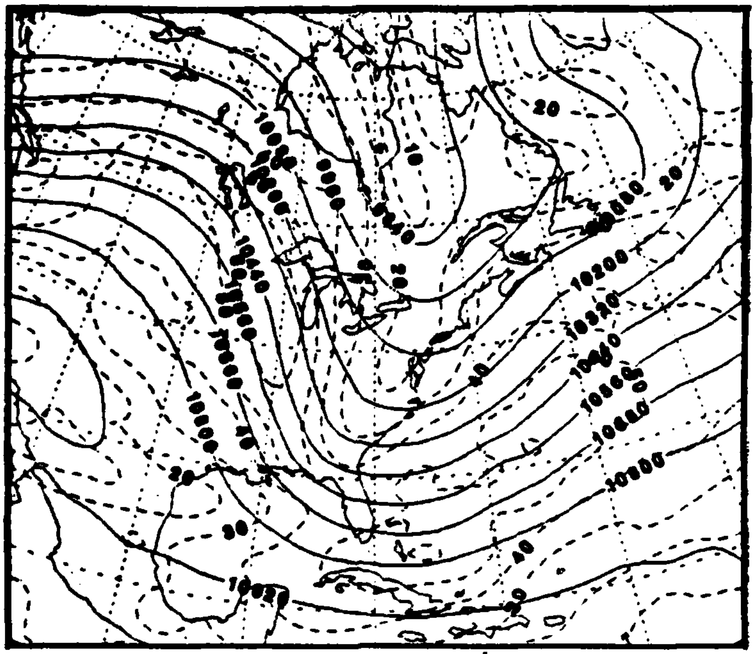

Figure 3.12 250 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 250 mb valid 1200 GMT 25 February 1986.

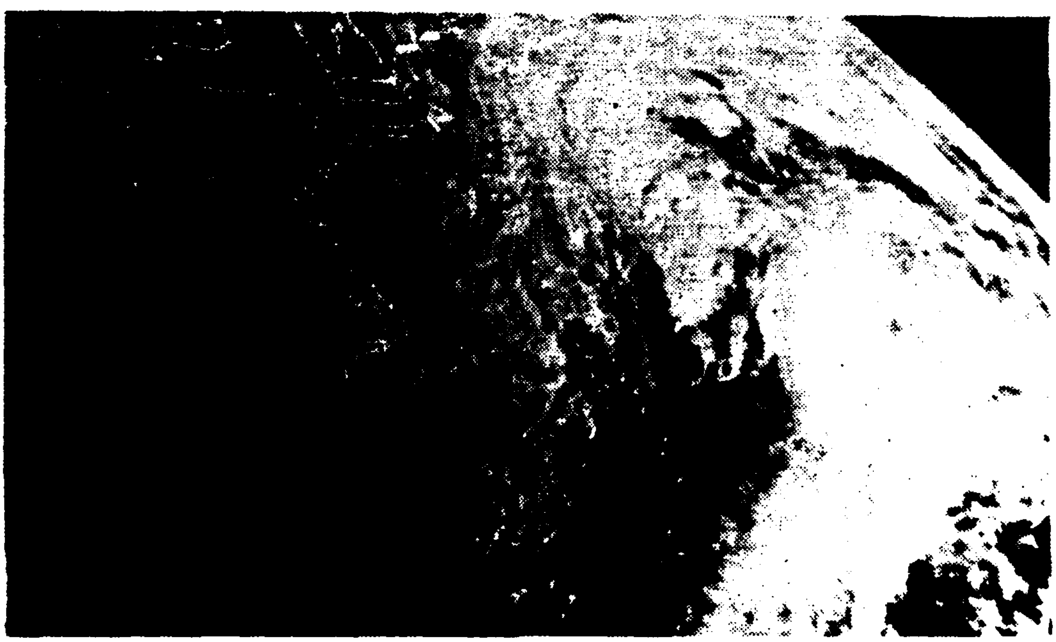

Figure 3.13 GOES visible satellite image valid 1231 GMT 25 February 1986.

The Air Force flew a dropsonde mission (no winds) that deployed seven dropsondes between 0855 GMT to 1606 GMT 25 February. The overwater aircraft track extended from Jacksonville FL east-northeastward to 35°N, 70°W, northward to 39°N, 71°W, northeastward to 42°N, 67°W, and westward to Nantucket, MA. These dropsondes are located behind the analyzed position of the westernmost cold front (Fig. 3.14). One sonde was dropped at 1250 GMT approximately 100 n mi from the NMC analyzed low pressure center of the first cyclone. These dropsonde observations will further define middle and lower tropospheric conditions in the area of cyclogenesis.

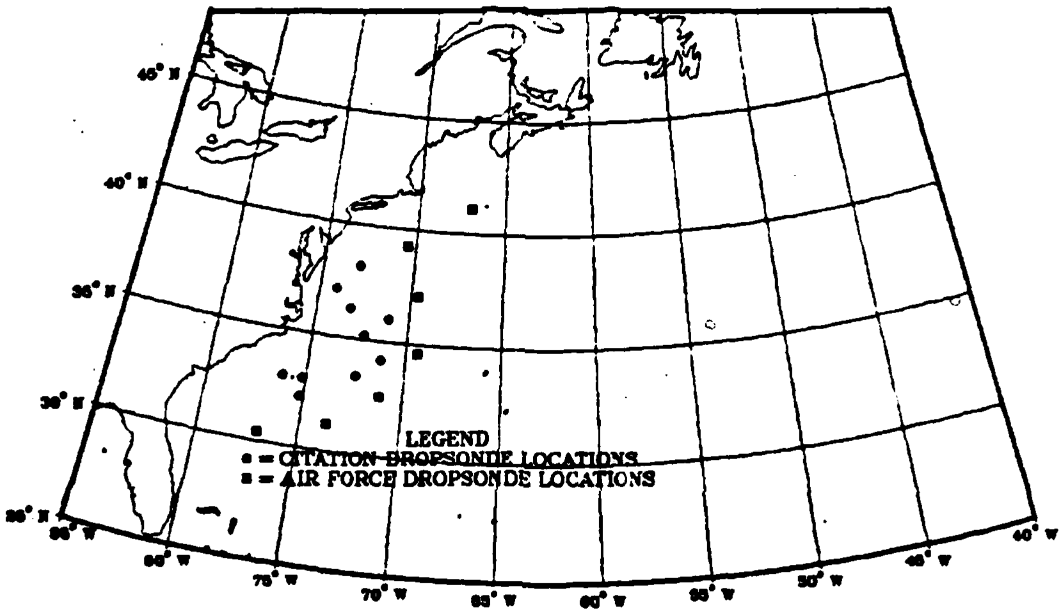

Figure 3.14 Location of Air Weather Service and Citation dropwindsonde observations on 25 February 1986 in support of GALE AWS between 0855 and 1606 GMT, Citation between 0820 and 1730 GMT.

D. 0000 GMT 26 FEBRUARY 1986

Rapid development continues over the western North Atlantic Ocean. At 500 mb, a closed circulation with a 516 dm center developed over Quebec (Fig. 3.15). Two 500 mb short-wave troughs are of interest at this time. The trough associated with the explosively deepening first cyclone extends southeastward to approximately 35°N, 68°W. The second trough axis extends along 75°W between 25°N and 35°N. The vorticity maximum associated with this trough consists of an elongated area of positive

vorticity ($+16 \times 10^{-5}s^{-1}$) from coastal Georgia northeastward to 43°N, 60°W, and then seaward of Nova Scotia. A strong ($+20 \times 10^{-5}s^{-1}$) absolute vorticity maximum associated with the first trough is located inside the elongated maximum northeast of the trough at 42°N, 60°W. This strong vorticity maximum combined with strong 500 mb flow produces significant PVA upstream from the surface cyclone. These vorticity patterns are somewhat complex but are in good agreement with the NMC vorticity analysis (not shown).

The NORAPS sea-level pressure analysis shows the low pressure center has moved rapidly northward to 40°N, 62°W and deepened to 986 mb (Fig. 3.16). The NMC hand analysis (not shown) continues to indicate two low pressure centers separated by 6° of latitude. The northernmost center near 42°N, 60°W deepened 27 mb in 24 h, which exceeds the explosive deepening criteria (Sanders and Gyakum, 1980). This 980 mb center which explosively deepened is located at 42.0°N, 59.7°W. It is incorrectly associated in the NMC analysis history with the cyclone that originally developed as a wave on the tail of the cold front. Tracks of the two IOP 9 cyclones were inferred from careful examination of available GOES satellite imagery (Fig. 3.17). The NORAPS center is located at 40°N, 62°W, which is approximately 2° of latitude southwest of the northernmost NMC center. The Block Island observation (43.9°N, 60.0°W) with a sea-level pressure of 988.6 mb, 40 kt winds from the east-northeast, rain, and pressure falling rapidly, locates the cyclone south of the island at 0000 GMT. The second NMC center (988 mb), which corresponds to the westernmost cyclone in the NMC analysis, is located at 37.5°N, 63.5°W, which is 3° of latitude southwest of the NORAPS center. The cold fronts associated with the two NMC centers are analyzed as parallel and separated by two or three degrees of latitude. The eastern-most cold front is analyzed as strong, while the western-most cold front is analyzed as undergoing frontolysis. The sea-level pressure and 1000-500 mb thickness analyses indicate strong cold advection behind the fronts from Connecticut to Florida (Fig. 3.16).

While satisfactory GOES imagery was unavailable for 0000 GMT 26 February 1986, the GOES visible sector at 1830 GMT 25 February 1986 (Fig. 3.18) shows a clear signature of the continuing frontal wave development of the second cyclone in the vicinity of 37°N, 60°W. The cloud pattern associated with the explosively deepening cyclone is more difficult to discern. The surface low appears to be located at 39°N, 65°W with a dry slot to the east. The imagery indicates that the comma-shaped cloud

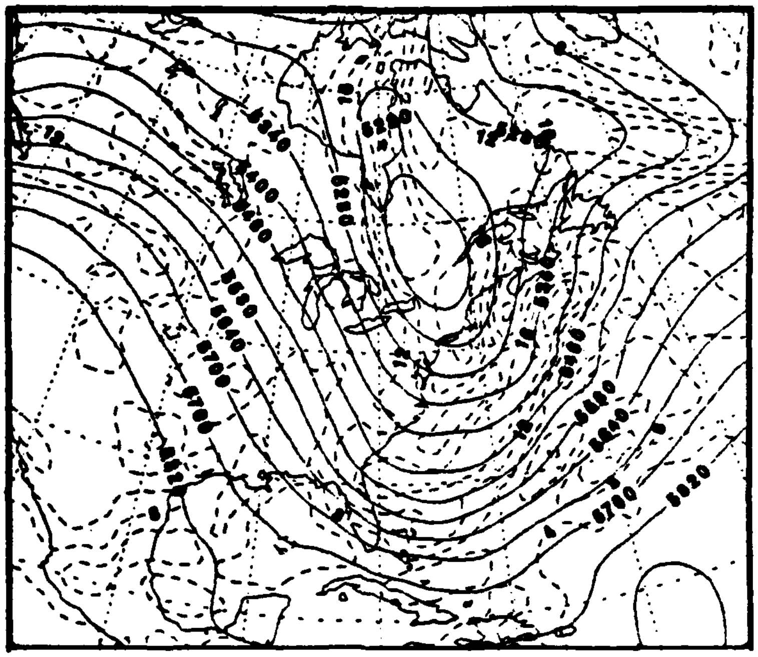

Figure 3.15 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) $10^{-5}\ s^{-1}$ valid 0000 GMT 26 February 1986.

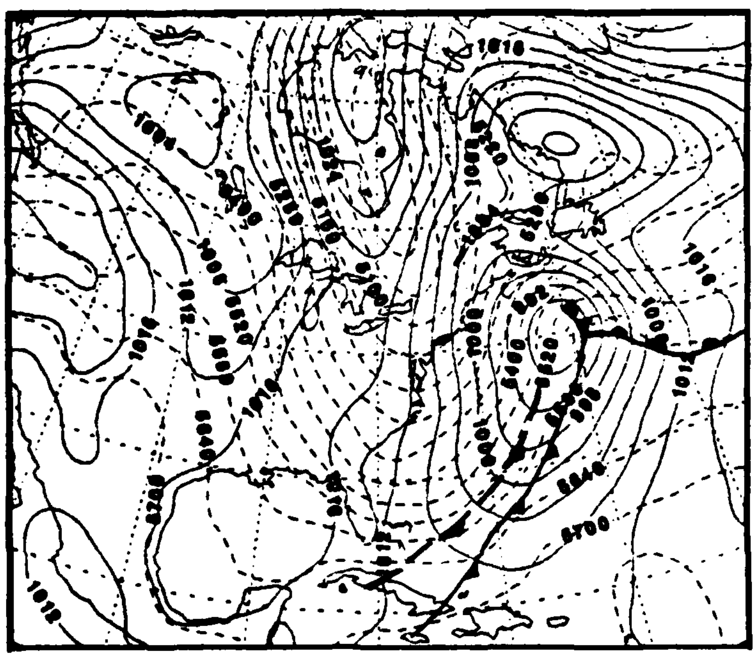

Figure 3.16 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 0000 GMT 26 February 1986.

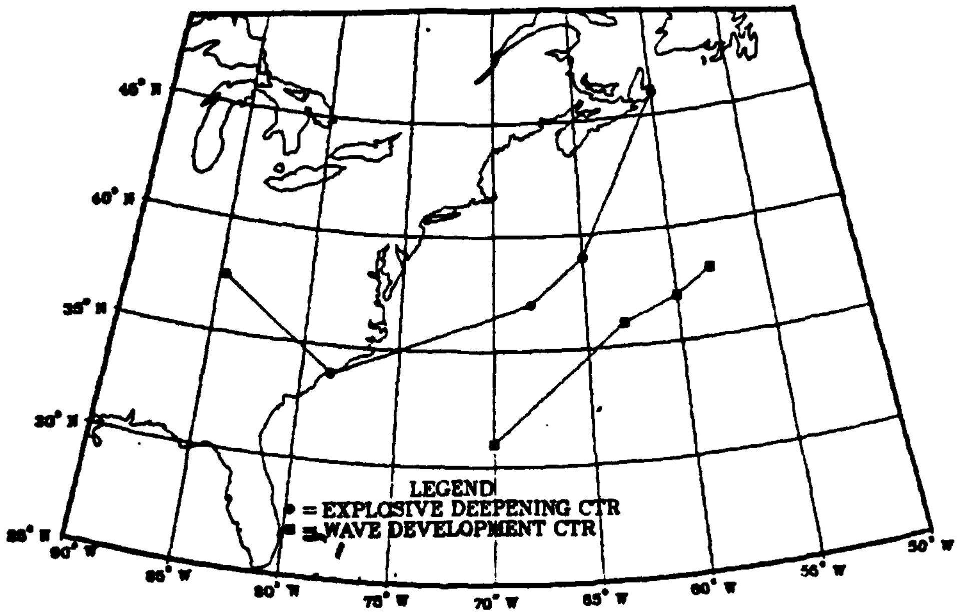

Figure 3.17 Tracks of two IOP 9 cyclones inferred from satellite observations Between 1200 GMT 24 and 1200 GMT 26 February 1986.

Figure 3.18 GOES visible satellite image valid 1830 GMT 25 February 1986.

feature along the East Coast continues to move northeastward. Close examination of the GOES imagery between 1200 GMT 25 and 0000 GMT 26 February clearly shows that the northern center in the NMC sea-level pressure analysis corresponds to the first cyclone, rather than the second cyclone that developed as a frontal wave. The second center in the NMC sea-level pressure analysis is not supported by data and does not correspond to any pressure centers detectable in the satellite imagery.

The 250 mb isotachs (Fig. 3.19) continue to show a broad 50 m s^{-1} jet maximum upstream of the explosive deepening cyclone, although two imbedded 60 m s^{-1} jet maxima are present. The first jet maximum is centered east of Bermuda, which places the first cyclone in the left front quadrant of the jet streak. The second jet maximum is located east of the Bahamas in a position where it can enhance vertical motions in the newly formed comma cloud. No GALE aircraft flights were flown during this synoptic period.

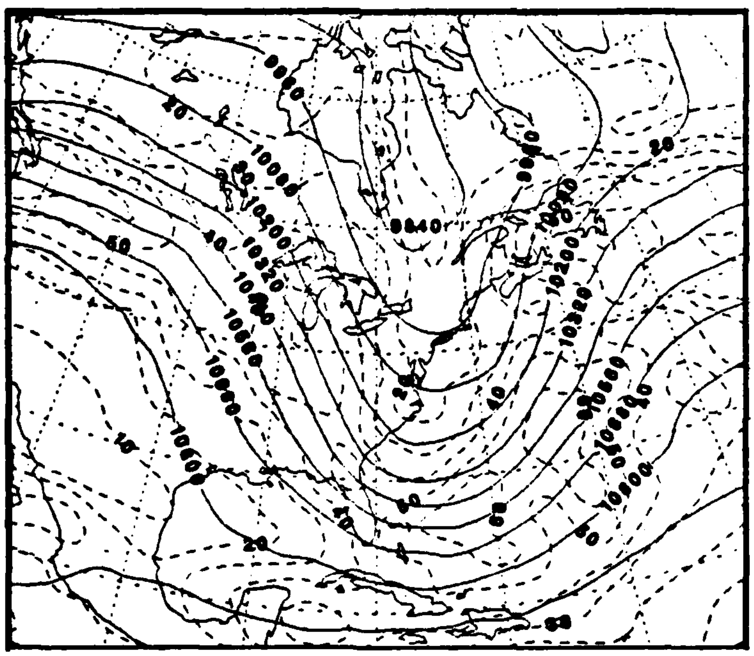

Figure 3.19 250 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 250 mb valid 0000 GMT 26 February 1986.

E. 1200 GMT 26 FEBRUARY 1986

During the last synoptic period of IOP 9, the dominant cyclone over Newfoundland deepens and the associated frontal system merges with that of the northward moving cyclone that originated as a wave on the tail of the cold front. The NORAPS 500 mb closed circulation moves northeastward, with a closed 510 dm center located over Maine (Fig. 3.20).

The NORAPS sea-level pressure analysis shows that the surface low at 40°N, 61°W continued to move northward to 46°N, 60°W (Fig. 3.21). The low has deepened from 980 mb to 971 mb in the previous 12 h. The western-most front that was analyzed by NMC as undergoing frontolysis 12 h earlier is now analyzed as a trough. The 1000-500 mb thickness field indicates strong baroclinity continues to exist in this system (Fig. 3.21).

The 250 mb analysis continues to show a broad 50 m s^{-1} jet maximum with embedded 60 m s^{-1} jet streaks along the axis from the Bahamas to Newfoundland (Fig. 3.22). This pattern is supported by four aircraft reports, two satellite cloud drift winds, and two rawinsonde observations along the jet axis.

The GOES visible imagery at 1330 GMT (Fig. 3.23) shows a strong low-level cold outbreak along the entire east coast of the United States with a well-defined cold front on the leading edge of the cold outbreak. Strong upper-level wind shear is indicated on the satellite imagery by the cirrus blowoffs from convective activity in the cold outbreak, and by a sharply defined cirrus shield on the cold air side of the front. This corresponds to the area of 60 m s^{-1} jet streaks in the 250 mb analysis (Fig. 3.22). The GOES IR imagery at 0630 and 0830 GMT (not shown) indicate merging of the two low pressure centers and associated fronts, which results in a single, well-organized, cyclonically-curved frontal band.

One GALE aircraft flight is available to supplement the 0000 GMT observations (GALE, 1986). The Air Force flew a dropsonde mission (no winds) that deployed 12 dropsondes between 1000 GMT and 1800 GMT 26 February. Some drops were within the inner closed sea-level pressure isobar of the dominant cyclone, southeastward of Nova Scotia (Fig. 3.24).

F. VERIFICATION OF NORAPS PROGNOSES FOR IOP 9

The NORAPS predictions were based on the 1200 GMT 24 February 1986 analyses, with outputs at 6-h increments to 48 h. This analysis time was chosen to

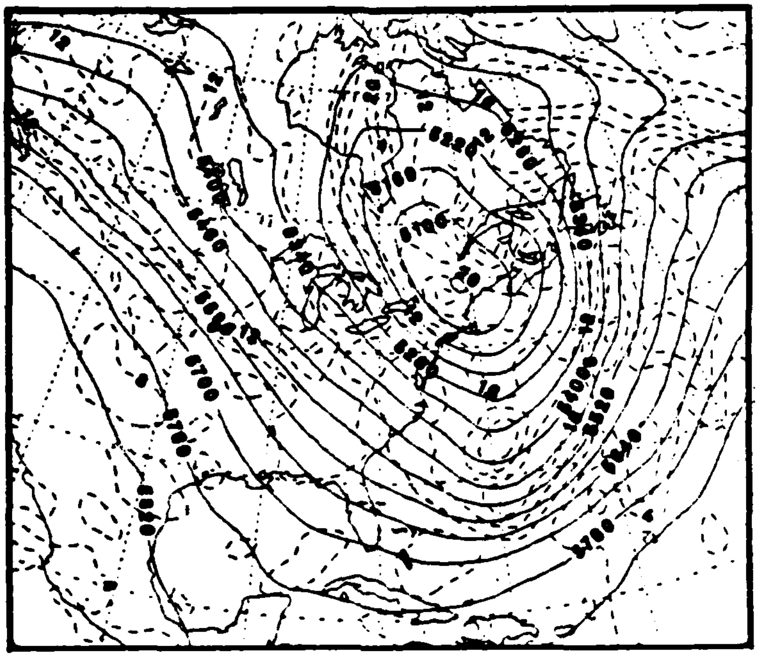

Figure 3.20 500 mb geopotential height analysis (solid) m and vorticity analysis (dashed) $10^{-5} s^{-1}$ valid 1200 GMT 26 February 1986.

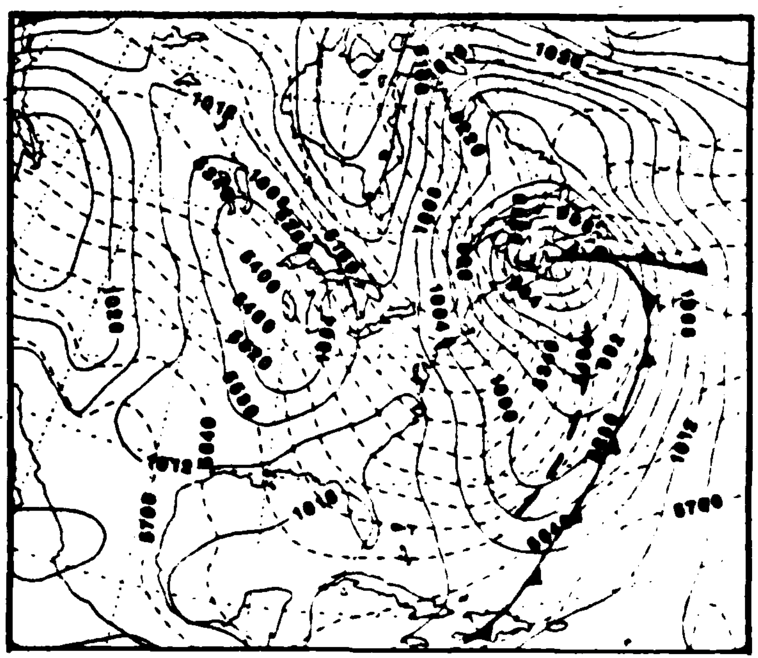

Figure 3.21 Sea-level pressure analysis (solid) mb and 1000-500 mb thickness (dashed) m valid 1200 GMT 26 February 1986.

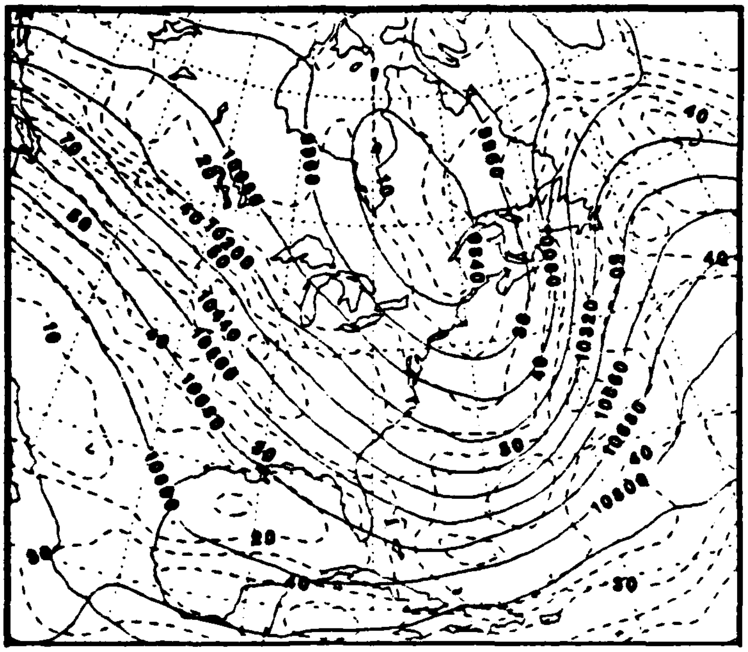

Figure 3.22 250 mb geopotential height analysis (solid) m and isotachs (dashed) m s^{-1} at 250 mb valid 1200 GMT 26 February 1986.

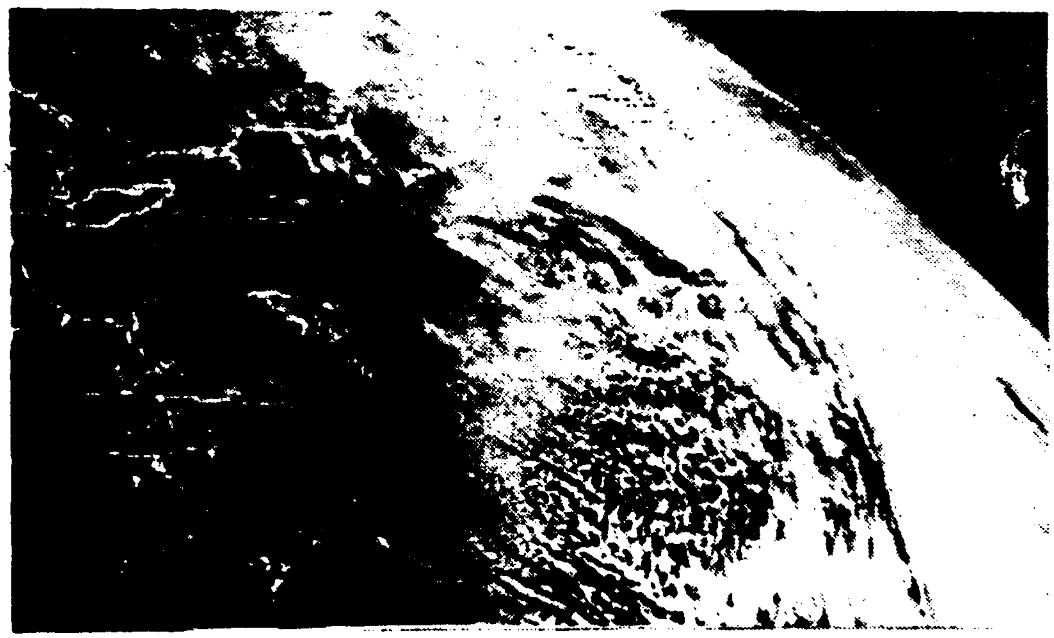

Figure 3.23 GOES visible satellite image valid 1330 GMT 26 February 1986.

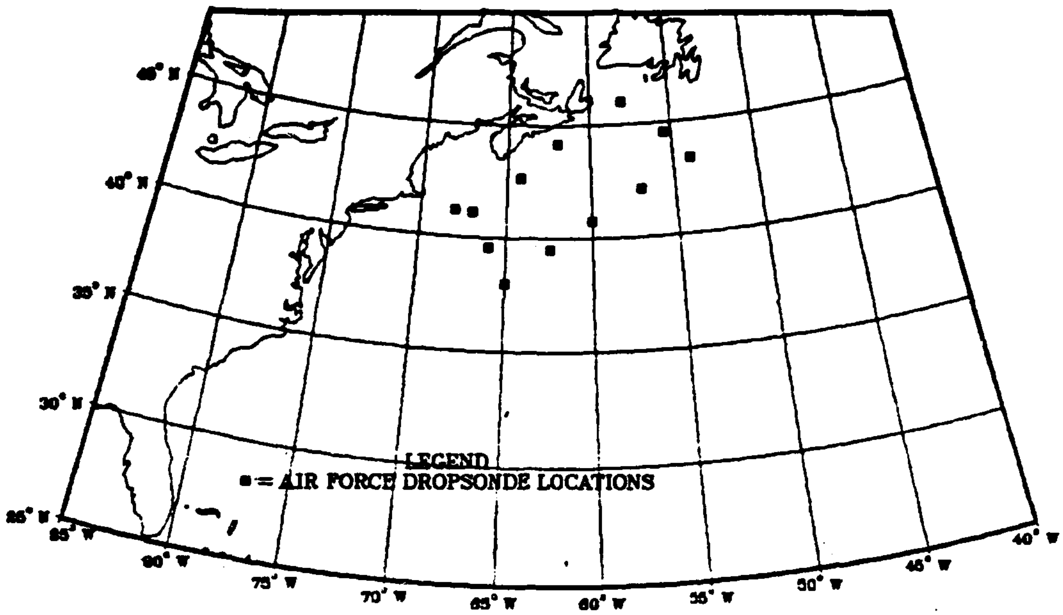

Figure 3.24 Location of Air Weather Service dropwindsonde observations on 26 February 1986 in support of GALE between 1000 and 1800 GMT.

make the 24-h and 48-h prognoses span the explosive deepening phase of the IOP 9 maritime cyclones.

1. **12 h prognosis VT: 0000 GMT 25 FEBRUARY 1986**

Only minor errors are evident in the 12-h forecast. At 500 mb, the forecast missed a short-wave perturbation along 70°W (Fig. 3.25). The location of the 500 mb long-wave trough over the East Coast as well as the short-wave trough over the Carolinas was well forecast. Height errors were generally less than 30 m (Fig. 3.26) with gradients and flow similar to those observed.

Although a closed circulation associated with maritime wave development off the Carolina coast was forecast, it was not as deep as analyzed (Fig. 3.27). One center was forecast, whereas separate centers occur in the NMC analysis as discussed previously. However, ridging along 90°W was well forecast, and errors were generally less than 2 mb (Fig. 3.28).

The 12 h forecast indicates an area of intense precipitation over central Cuba (Fig. 3.29). One minor area of convective precipitation is located in the forecast frontal trough northeast of the Bahamas, and another in the southerly flow in advance of the trough at 33°N. Both forecast areas of convective precipitation are supported

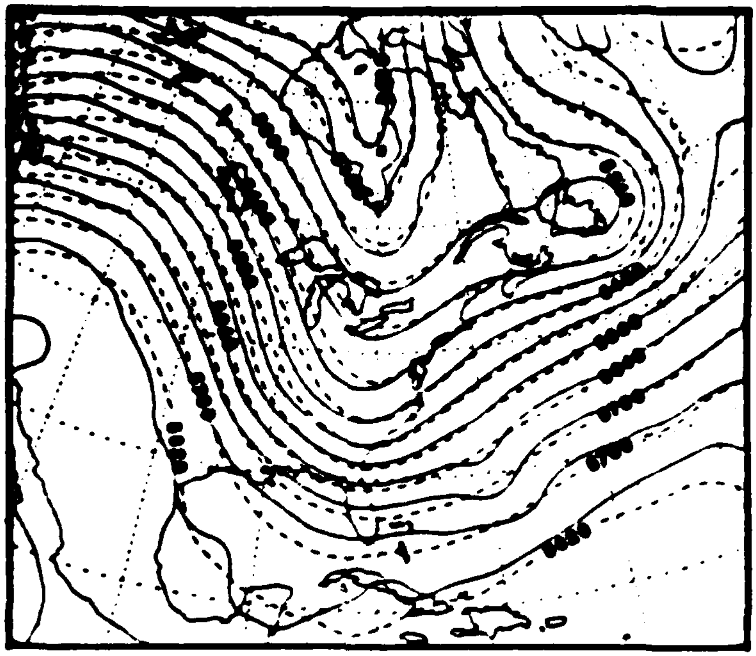

Figure 3.25 12 h 500 mb prognosis and analysis. Predicted (dashed) and verifying heights (solid) at 500 mb for 0000 GMT 25 February 1986.

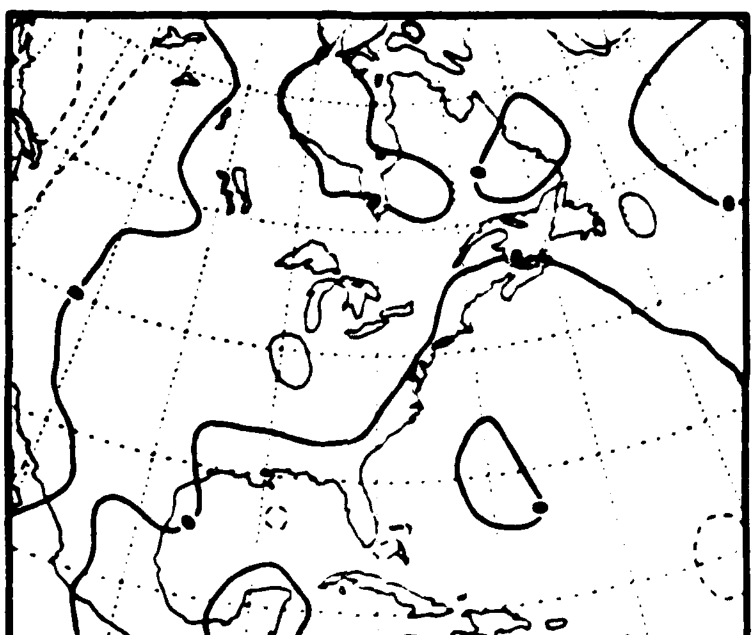

Figure 3.26 Predicted minus analyzed heights (m) at 500 mb. Positive(negative) values indicate predicted heights are larger (smaller) than analyzed values at 0000 GMT 25 February 1986.

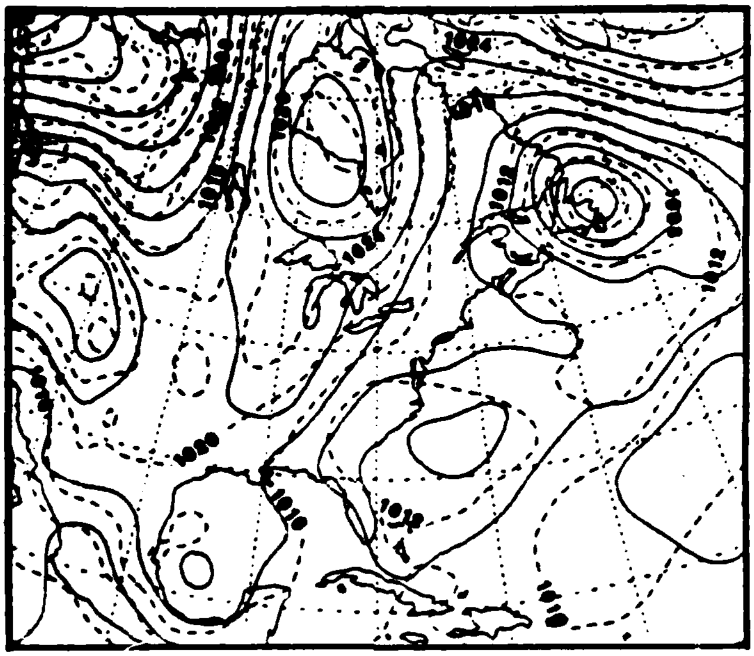

Figure 3.27 12 h sea-level pressure prognosis and analysis. Predicted (dashed) and verifying pressures (solid) at sea-level for 0000 GMT 25 February 1986.

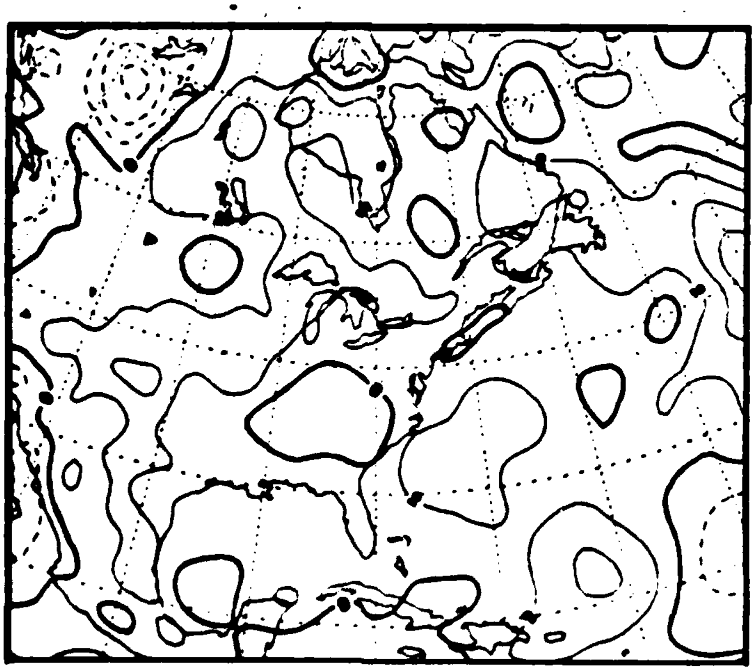

Figure 3.28 Predicted minus analyzed pressures (mb) at sea-level. Positive (negative) values indicate predicted pressures are larger (smaller) than analyzed values at 0000 GMT 25 February 1986.

by cloud activity in satellite imagery, and GALE aircraft reports support convective precipitation in the northernmost area. These convective precipitation areas are associated with strong PVA and low-level cold advection forecast north of the Bahamas. The forecast does not capture the precipitation associated with the front over the Carolina coast and troughing northward from North Carolina to Massachusetts. Precipitation over these areas is well supported by surface observations and clouds in the satellite imagery.

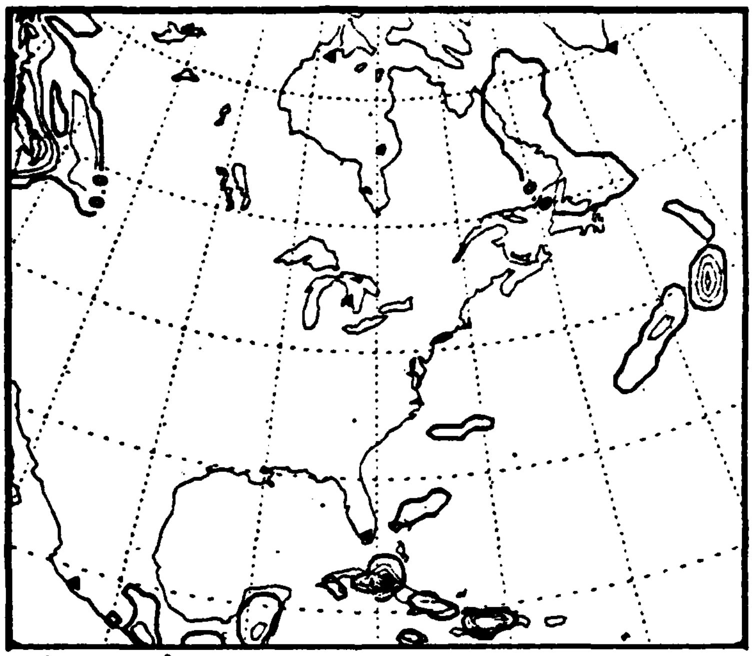

Figure 3.29 12 h forecast of total precipitation (cm) accumulated over the previous 12 h valid 0000 GMT 25 February 1986.

2. 24 h prognosis VT: 1200 GMT 25 FEBRUARY 1986

The 24-h 500 mb forecast correctly captured the amplification of the East Coast trough (Fig. 3.30). The forecast gradients and flow were were similar to those observed. However, the forecast trough was 30 m weaker than analyzed (Fig. 3.31).

The 24-h sea-level pressure forecast has the maritime cyclone position within 4° of latitude (240 n mi) of the position in the NORAPS analysis (Fig. 3.32). However, the presence of two distinct cyclones in the final NMC analysis at 1200 GMT is not reflected in the NORAPS forecast (or analysis). The central pressure was 8 mb higher in the forecast than the analysis (Fig. 3.33). While the shape of the circulation was

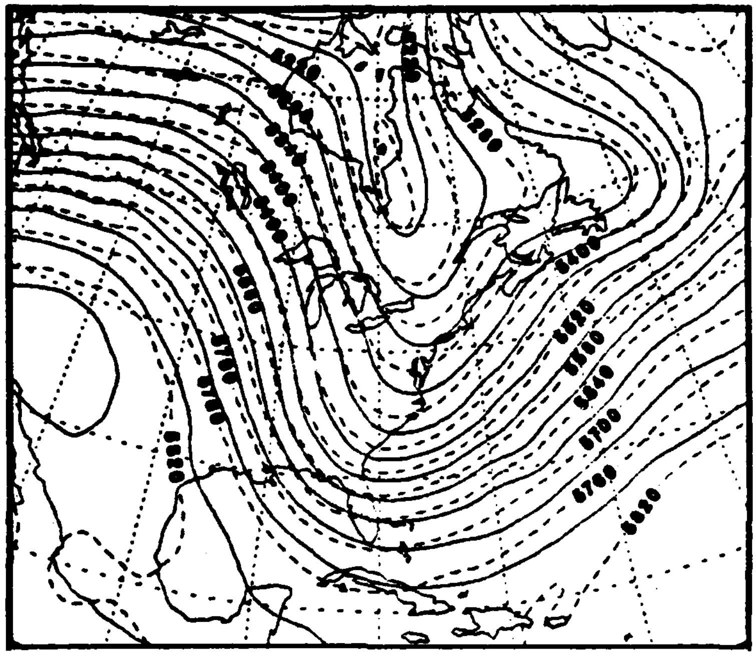

Figure 3.30 24 h 500 mb prognosis and analysis. Predicted (dashed) and verifying heights (solid) at 500 mb for 1200 GMT 25 February 1986.

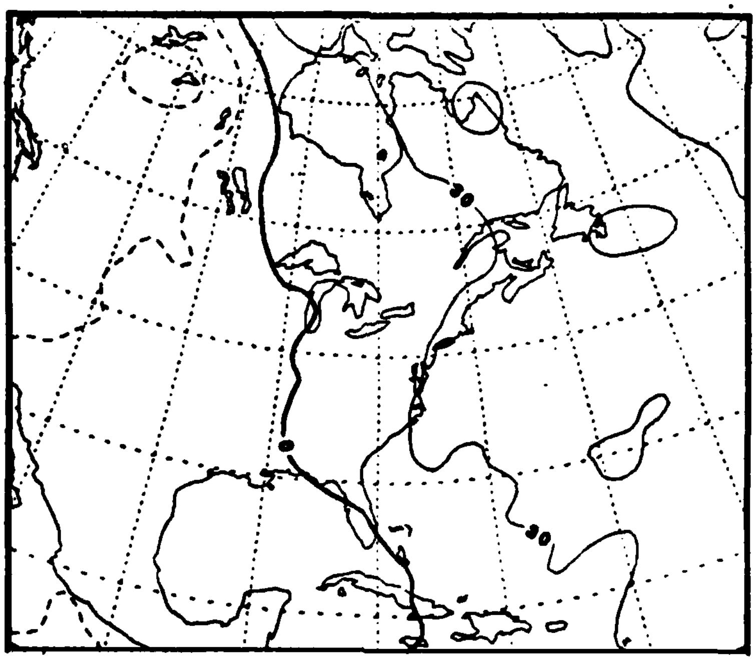

Figure 3.31 Predicted minus analyzed heights (m) at 500 mb. Positive(negative) values indicate predicted heights are larger (smaller) than analyzed values at 1200 GMT 25 February 1986.

well represented in the forecast, the gradients are significantly weaker. Weaker gradients cause the model to under-forecast the warm and cold advection associated with this wave.

The 24-h forecast shows a precipitation band extending northeastward from western Cuba, with one area of intense precipitation north of Cuba and another centered at 30°N, 70°W. Strong low-level cold advection and moderate PVA were forecast over the area of intense precipitation centered at 30°N, 70°W, in advance of the forecast surface trough off the Carolina coast. This forecast precipitation has little contribution from convective precipitation in the model. The precipitation centered at 30°N, 70°W occurs at the same location as the clouds associated with the frontal wave in the satellite imagery (Fig. 3.13). The forecast does not capture precipitation observed from New Brunswick southwestward to Long Island associated with the northern explosively deepening cyclone (Fig. 3.34).

3. **36 h prognosis VT: 0000 GMT 26 FEBRUARY 1986**

The quality of the forecast begins to degrade seriously at 36 h. The forecast does not capture the existence of a short-wave trough extending from Massachusetts southeastward to 36°N, 60°W (Fig. 3.35). As a result, forecast heights were 90 m too high southeast of Massachusetts (Fig. 3.36). At 500 mb, the forecast trough along the East Coast is sharper and has a greater amplitude.

At the surface, the forecast location of the cyclone center is 3° of latitude southwest of the observed center (Fig. 3.37). The forecast central pressures were 12 mb higher than analyzed (Fig. 3.38). The frontal trough moved much faster than forecast, which agrees with the differences in the 500 mb trough amplitude and position. Therefore, the offshore flow in the forecast was much weaker than observed.

The 36 h forecast shows an intense precipitation maximum in advance of the forecast surface frontal trough (Fig. 3.39). Satellite imagery indicates a well organized frontal type cloud band extended over this area during the past twelve hours (Figs. 3.13 and 3.18). This precipitation is associated with moderate low-level cold advection forecast into the frontal trough and warm advection in advance of the trough. An area of weaker, predominantly convective, precipitation is forecast off the Carolina coast. Cloud activity apparent in GOES satellite imagery also supports this precipitation maximum (Figs. 3.13 and 3.18). This precipitation is associated with strong PVA and low-level cold advection forecast in that area. The region of precipitation north of the intense cyclone is poorly forecast by the NORAPS model.

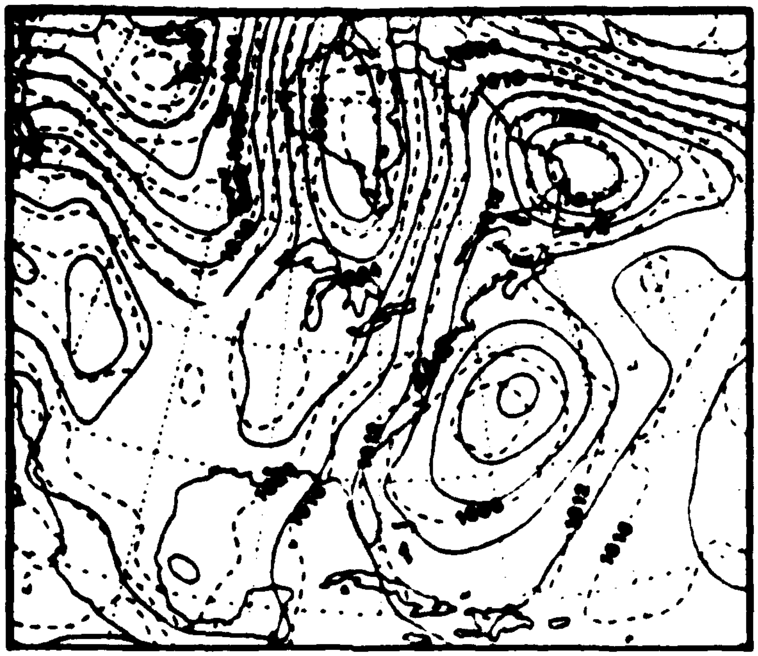

Figure 3.32 24 h sea-level pressure prognosis and analysis. Predicted (dashed) and verifying pressures (solid) at sea-level for 1200 GMT 25 February 1986.

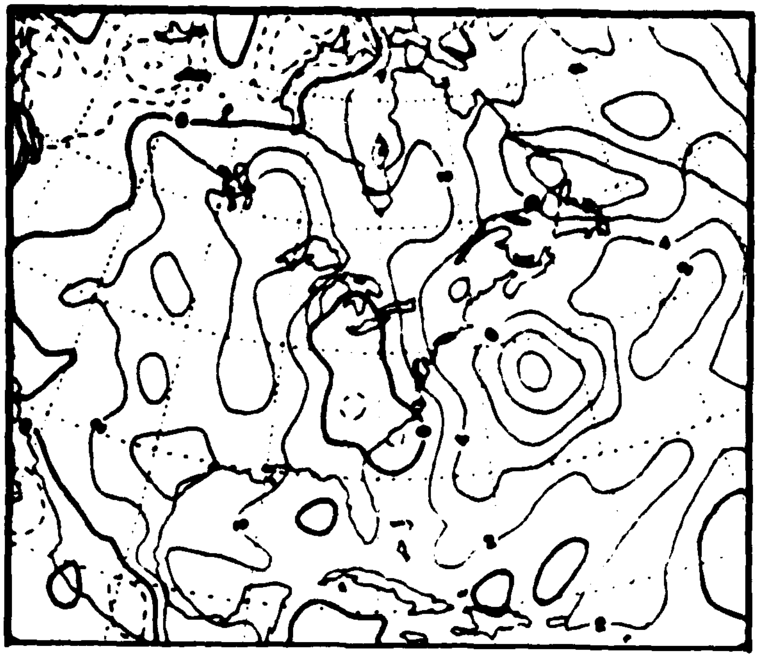

Figure 3.33 Predicted minus analyzed pressures (mb) at sea-level. Positive (negative) values indicate predicted pressures are larger (smaller) than analyzed values at 1200 GMT 25 February 1986.

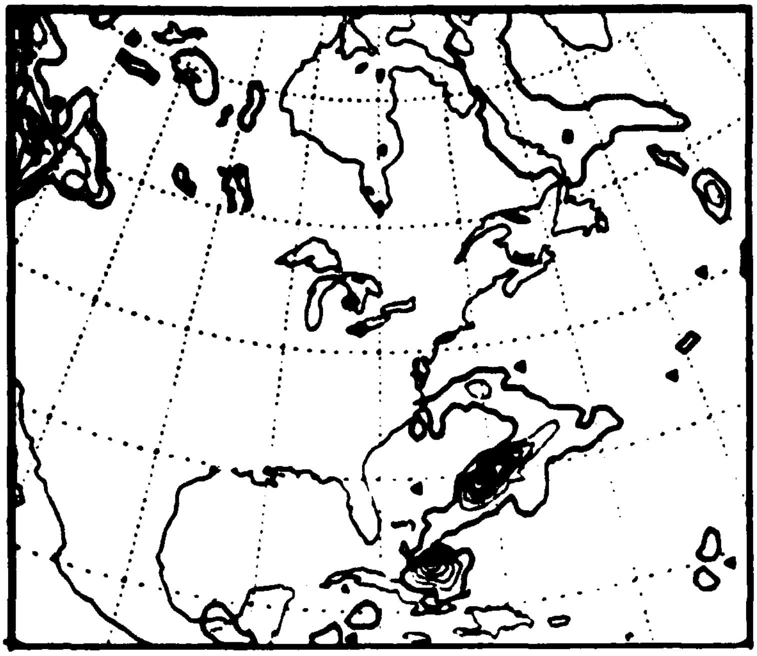

Figure 3.34 24 h forecast of total precipitation (cm) accumulated over the previous 12 h valid 1200 GMT 25 February 1986.

4. 48 h prognosis VT: 1200 GMT 26 FEBRUARY 1986

The previously discussed NORAPS errors continue to increase in the 48 h forecast (Fig. 3.40). The forecast long-wave trough movement was slower than analyzed, accounting for most of the 150 m error east of the analyzed trough. Height errors as large as 150 m are observed over western Canada at 500 mb (Fig. 3.41). These errors are associated with a forecast ridge along 110°W being stronger than analyzed (Fig. 3.40).

Although the forecast location of the surface cyclone is within 3° of latitude south of the observed location (Fig. 3.42), the errors in central pressure continue to be on the order of 12 mb (Fig. 3.43). The slower movement of the surface cyclone in the forecast is consistent with the slower movement of the 500 mb trough in the forecast. The forecast position of the surface trough along 65°W is actually better in the 48 h forecast than in the 36 h forecast (Figs. 3.37 and 3.42).

The 48 h forecast shows an area of intense precipitation in advance of the forecast surface frontal trough with approximately equal contributions from convective and non-convective precipitation in the model (Fig. 3.44). Another area of intense precipitation, which is located over low-level southerly flow forecast south of

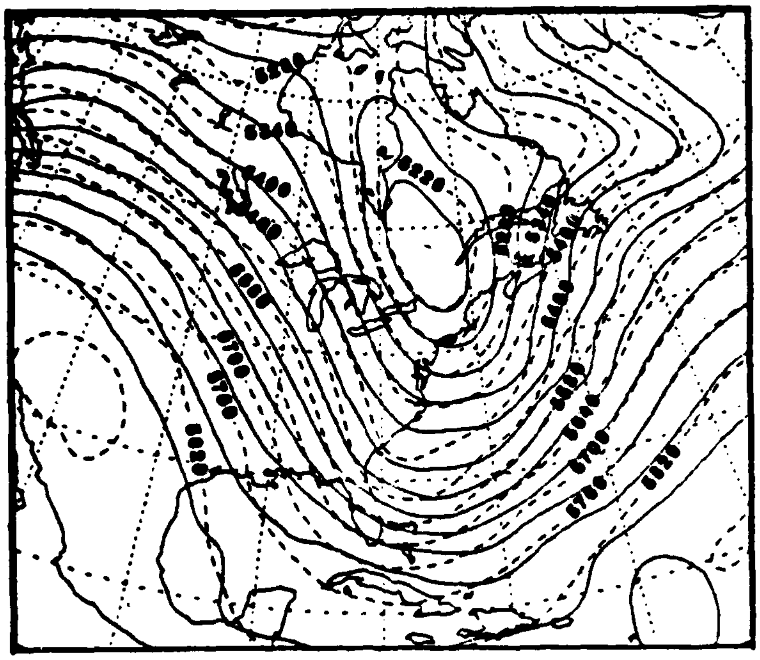

Figure 3.35 36 h 500 mb prognosis and analysis. Predicted (dashed) and verifying heights (solid) at 500 mb for 0000 GMT 26 February 1986.

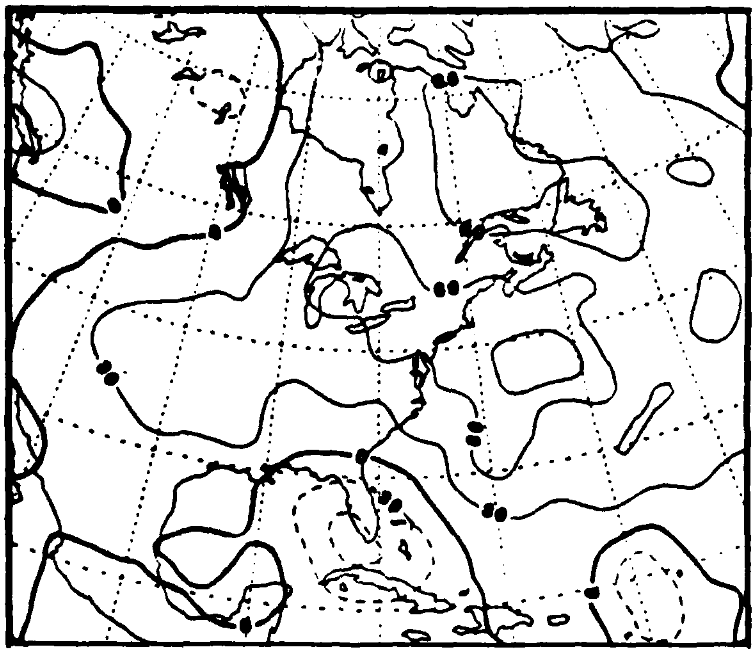

Figure 3.36 Predicted minus analyzed heights (m) at 500 mb. Positive(negative) values indicate predicted heights are larger (smaller) than analyzed values at 0000 GMT 26 February 1986.

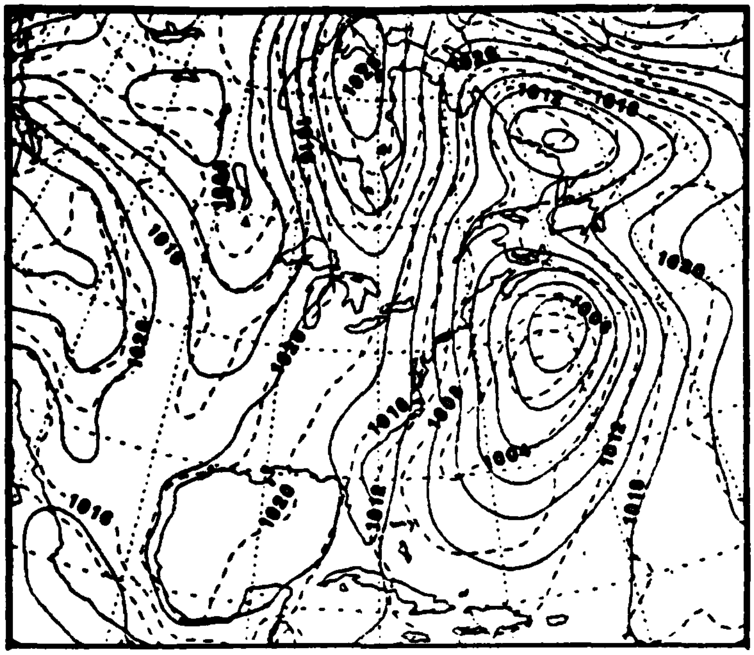

Figure 3.37 36 h sea-level pressure prognosis and analysis. Predicted (dashed) and verifying pressures (solid) at sea-level for 0000 GMT 26 February 1986.

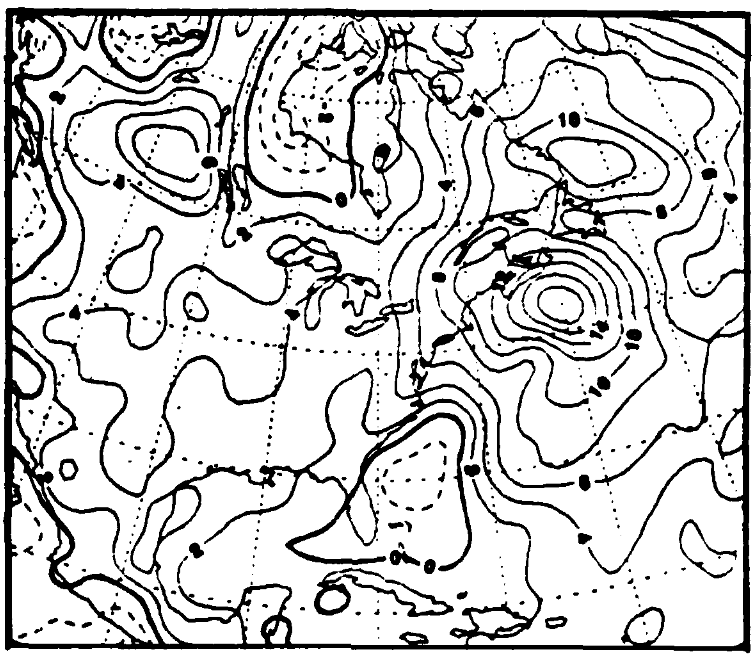

Figure 3.38 Predicted minus analyzed pressures (mb) at sea-level. Positive (negative) values indicate predicted pressures are larger (smaller) than analyzed values at 0000 GMT 26 February 1986.

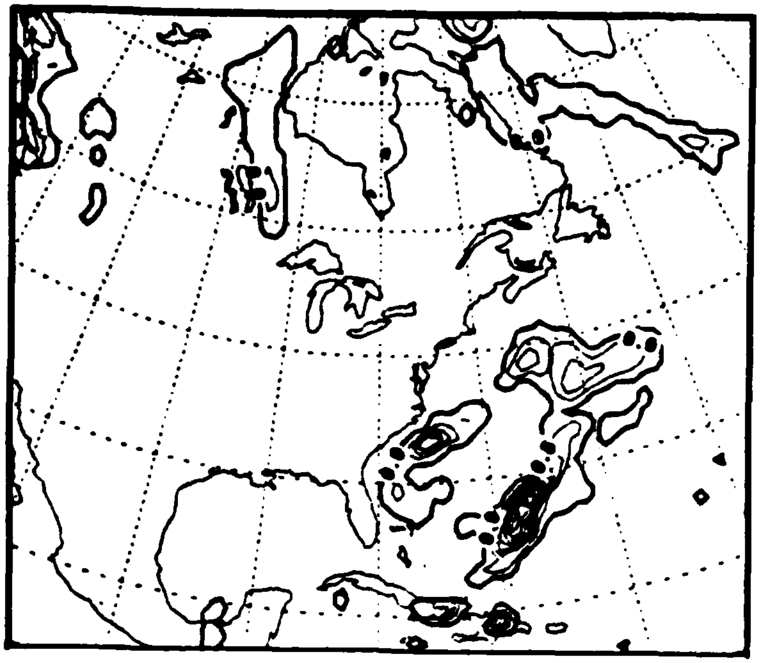

Figure 3.39 36 h forecast of total precipitation (cm) accumulated over the previous 12 h valid 0000 GMT 26 February 1986.

Newfoundland, had little contribution from convective precipitation in the model. Minor maximums in the cold air behind the forecast frontal trough are predominantly convective in nature. These forecast precipitation maximums are in general agreement with observed cloud patterns in the GOES satellite imagery (Figs. 3.18 and 3.23).

5. Summary of NORAPS verification for IOP 9

While the NORAPS model seemed to forecast the movement of an explosively deepening cyclone well(Fig. 3.45), a closer analysis reveals less success. The NORAPS model appears successful because both the NORAPS analysis and forecasts missed the double low structure and associated upper-level features. As a result of the sparsity of observations, both the NORAPS analysis and forecasts described one surface cyclone in the western North Atlantic. More detailed analyses indicated two surface cyclones in satellite imagery and also in the NMC final surface analyses for IOP 9. The NORAPS stormtrack that was forecast is almost the mean of two stormtracks inferred from satellite observations (Fig. 3.46).

The NORAPS model forecast the tendency, but not the extent of surface deepening. The 12 h forecast was already 4 mb too weak, and by 48 h the forecast pressure was 16 mb higher than analyzed (Fig. 3.47). The corresponding NMC hand

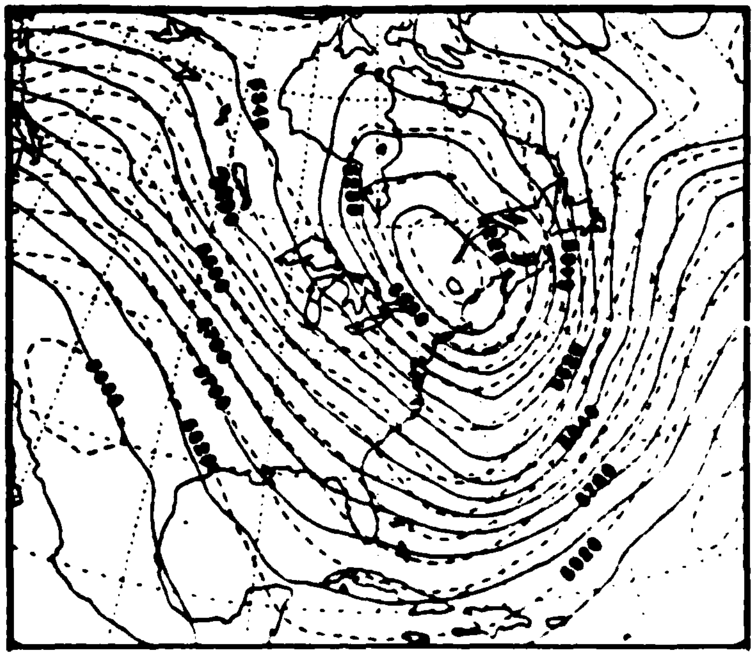

Figure 3.40 48 h 500 mb prognosis and analysis. Predicted (dashed) and verifying heights (solid) at 500 mb for 1200 GMT 26 February 1986.

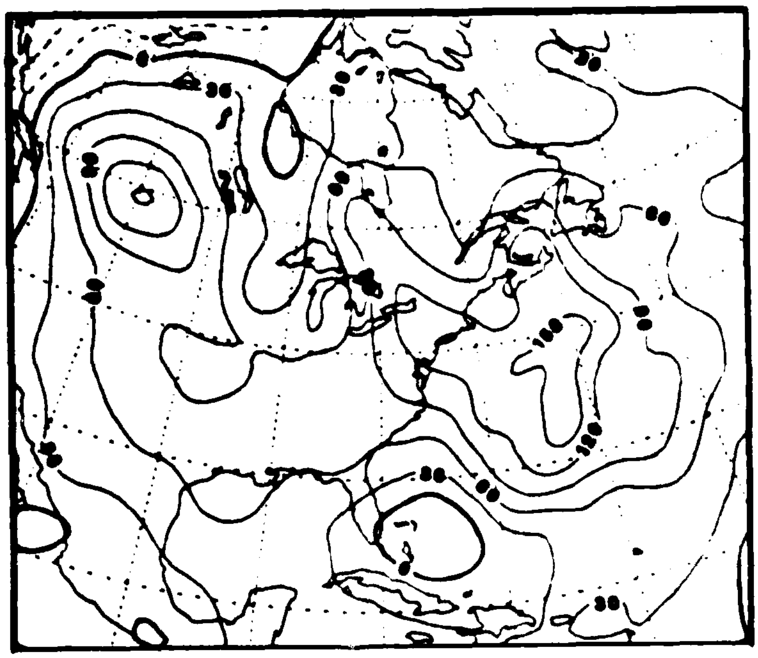

Figure 3.41 Predicted minus analyzed heights (m) at 500 mb. Positive(negative) values indicate predicted heights are larger (smaller) than analyzed values at 1200 GMT 26 February 1986.

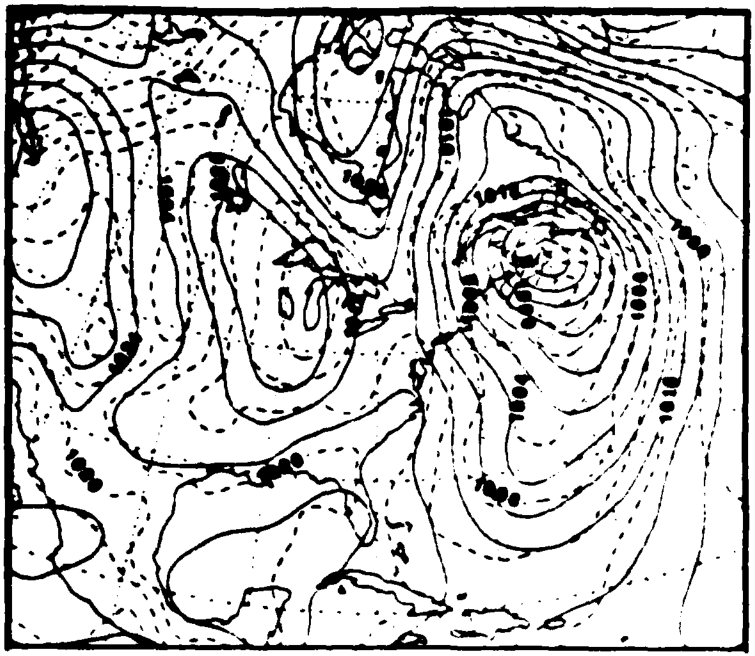

Figure 3.42 48 h sea-level pressure prognosis and analysis. Predicted (dashed) and verifying pressures (solid) at sea-level for 1200 GMT 26 February 1986.

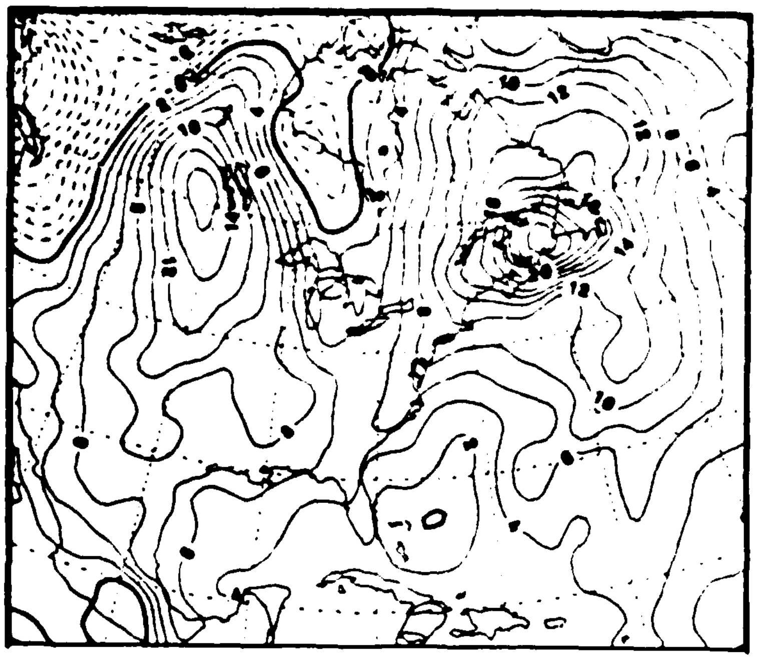

Figure 3.43 Predicted minus analyzed pressure (mb) at sea-level. Positive (negative) values indicate predicted pressures are larger (smaller) than analyzed values at 1200 GMT 26 February 1986.

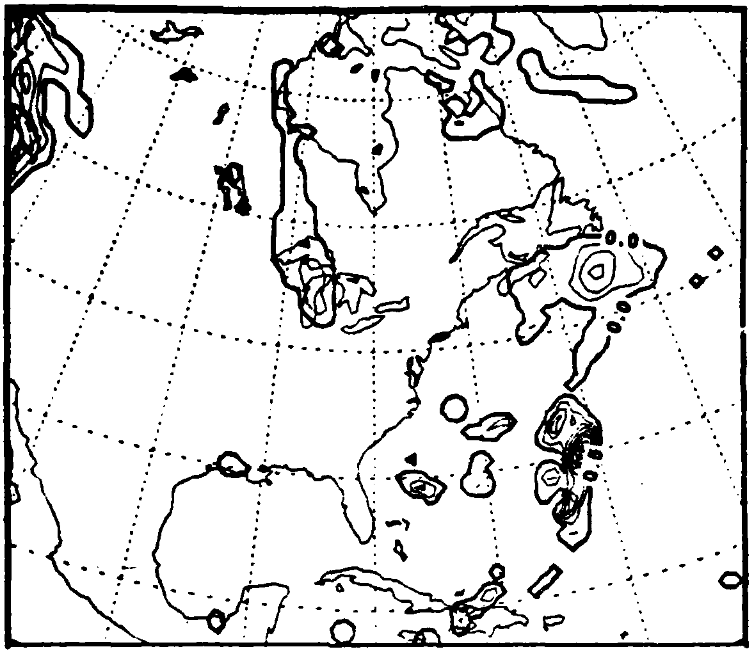

Figure 3.44 48 h forecast of total precipitation (cm) accumulated over the previous 12 h valid 1200 GMT 26 February 1986.

analysis at 48 h (not shown) was 3 mb deeper than the NORAPS analysis and 19 mb deeper than the NORAPS 48 h forecast.

The NORAPS 500 mb geopotential height forecasts were successful through 36 h. The major error was too much of amplitude and too slow of movement in the primary shortwave that moved off the East Coast. The positive error associated with this phase error grows to 90 m at 36 h and 150 m at 48 h.

The NORAPS precipitation forecasts captured the precipitation associated with the southern frontal wave development reasonably well. However, precipitat[illegible] associated with the explosively deepening cyclone was not forecast [illegible] surprising in light of the fact that the NORAPS analyses and forecast failed [illegible] two separate surface cyclone systems or the details of the upper leve[illegible] produced two distinct systems.

G. SUMMARY OF IOP 9 CYCLOGENESIS

Cyclogenesis in IOP 9 involved two separate [illegible] IOP. The first cyclone associated with the [illegible] the dominant system. This surface [illegible]

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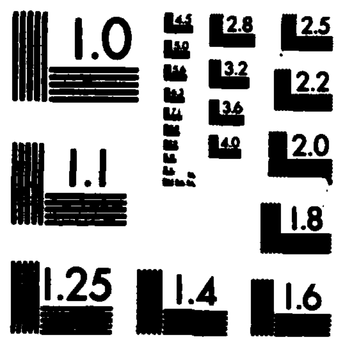

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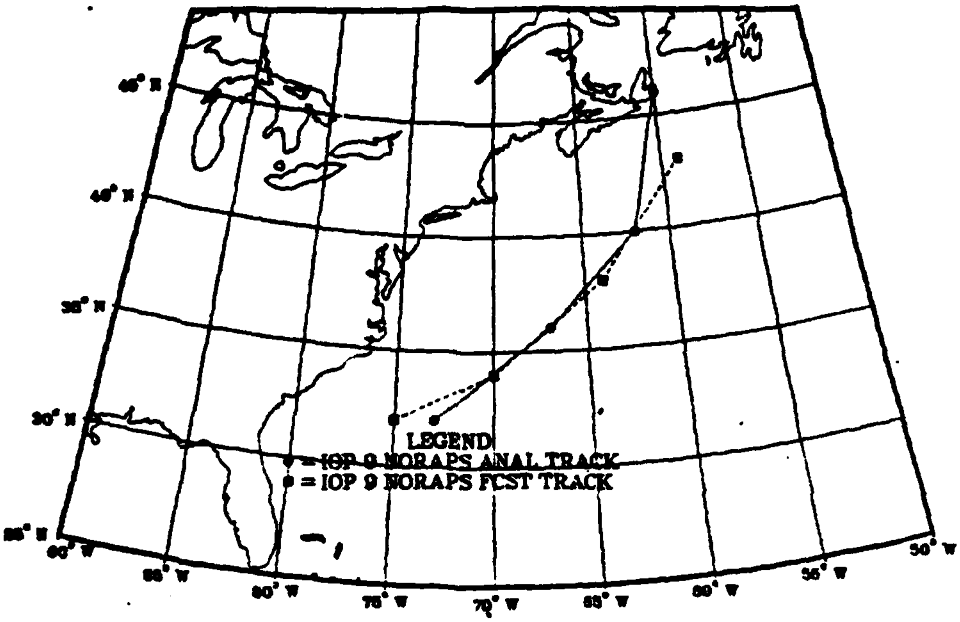

Figure 3.45 Forecast (dashed) and analyzed (solid) tracks of IOP 9 cyclones between 1200 GMT 24 and 1200 GMT 26 February 1986.

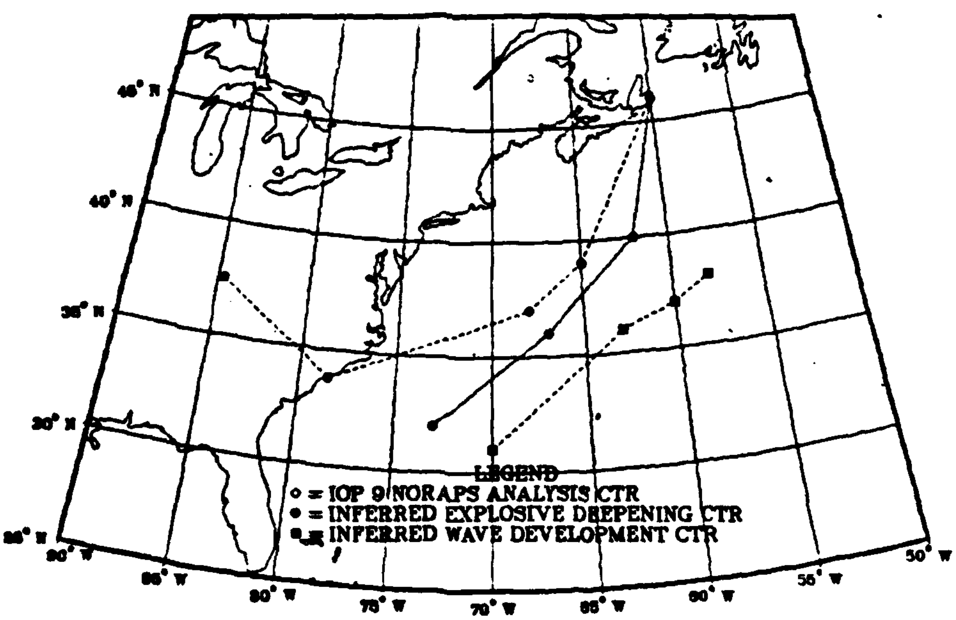

Figure 3.46 Analyzed (solid) and inferred (dashed) tracks of IOP 9 cyclones between 1200 GMT 24 and 1200 GMT 26 February 1986.

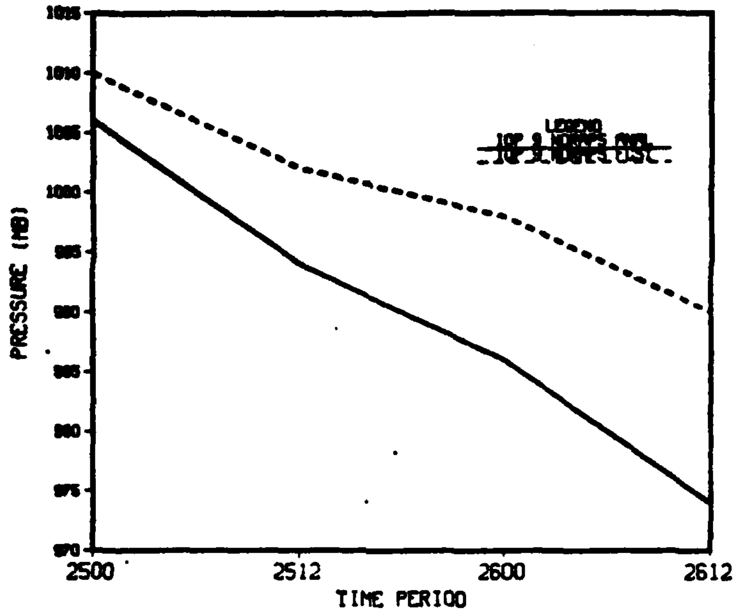

Figure 3.47 Forecast (dashed) and analyzed (solid) pressure of IOP 9 cyclones between 1200 GMT 24 and 1200 GMT 26 February 1986.

moved eastward to the Carolina coast. Upon reaching the coast it deepened explosively as it moved rapidly northeastward to Nova Scotia. Between 0000 GMT and 1200 GMT 25 February, the PVA northeast of the Virginia coast apparently was a key factor in contributing to the rapid deepening as the cyclone moved northeastward over the Gulf Stream. This system was the only explosively deepening maritime cyclone of the GALE experiment.

The second cyclone developed as a wave on a trailing cold front east of Florida. A subtropical jet stream over the cold front in the North Atlantic apparently contributed to the wave development east of the Bahamas by 0000 GMT 25 February. This cyclone deepened and moved quickly northeastward. The subtropical jet streak may have continued to support the development and movement of the frontal wave until the end of the second synoptic period. After the initial rapid movement and deepening, the frontal wave slowed and merged with the stronger cyclone to the west.

The incipient short-wave cyclone of IOP 9 passed directly through the CLASS and 3 h supplemental NWS rawindsonde network and PAM network of the GALE project. This dense network of observations will provide an excellent three-dimensional picture of the structure of this cyclone prior to movement offshore and subsequent explosive cyclogenesis.

Citation dropsondes during the first and second synoptic periods were strategically located to observe the coastal marine atmosphere in advance of the dominant cyclone system. This cyclone system exhibited limited deepening until it crossed the Carolina coast into this marine atmosphere. These soundings will provide an excellent opportunity to describe an atmosphere that was conducive to explosive cyclogenesis.

Air Weather Service and Citation dropsondes during the second and third synoptic periods were strategically located to facilitate investigation of the cold advection associated with the explosively deepening cyclone. This dense matrix of sounding observations will contribute significantly to re-constructing the three-dimensional structure of an explosively deepening cyclone. Data from additional GALE aircraft flights investigating rainbands and the boundary layer over the Gulf Stream may prove useful in studying the low tropospheric structure in advance of the incipient cyclone, contributing to further understanding of the explosive deepening cyclone of IOP 9.

IV. CONCLUSIONS AND RECOMMENDATIONS

A synoptic diagnosis of cyclogenesis and verification of NORAPS model forecasts was conducted for IOP's 1 and 9 in the GALE project. This GALE study was directed toward the study of the important synoptic and subsynoptic features of IOP 1 and 9. A detailed discussion of the key synoptic and subsynoptic features important to coastal and ocean cyclogenesis were described. Operationally available NORAPS analyses were carefully examined and compared with manually analyzed NMC sea-level pressure, LFM upper-air analyses, and GOES satellite imagery. Some supplemental GALE data were investigated to clarify understanding of key features. The applications of supplemental GALE data set coverage to future investigation of IOP 1 and 9 were discussed.

A verification of the NORAPS numerical prognoses was conducted for IOP 1 and 9. This verification consisted of comparison of the NORAPS forecasts with the verifying NORAPS analyses. Differences between NORAPS forecasts and analyses were also computed and plotted.

In both IOP's there was significant interaction between two separate systems during cyclogenesis. The two short-wave trough systems of IOP 1 interacted in a manner that decreased the rate of cyclogenesis of the second system. The first shortwave initiated a surface trough over the Carolina coast that significantly altered the warm air advection in advance of the second system. Low level southerly flow east of the trough advected warmer and more moist air northward in advance of the second cyclone. This effectively reduced the sensible heat and moisture flux from the sea surface in the warm sector of the second cyclone. Significant warm advection occurred north of the surface low center, rather than east or northeast of the center. As a result,the area of PVA was not coincident with the area of low-level warm advection, and the vertical motions associated with PVA and low-level warm advection did not reinforce each other sufficiently for explosive cyclogenesis.

The interaction between the two systems in IOP 9 is less clear. However, it is obvious that low latitude moisture was blocked from interacting with the explosively deepening cyclone by the frontal wave development to the southeast. The explosive cyclogenesis may have been even more intense if more moisture had been available to the cyclone.

The IOP 9 western cyclone did not deepen rapidly until reaching the coast and the enhanced low-level thermal and moisture gradients associated with the atmosphere over the Gulf Stream. The environment over the ocean had sufficient moisture and conditional instability to aid the rapid maritime cyclogenesis.

Although neither of these two IOP's described a classic East Coast storm, the two cases proved quite interesting. In both cases mesoscale structure was important in understanding the cyclogenesis event. The cyclogenesis of IOP 1 and 9 represent more complex interactions and processes than the simplified cyclogenesis suggested by the quasi-geostrophic theory.

The NORAPS model handled both cases of cyclogenesis reasonably well. The overall forecast of synoptic scale features was successful. The intensification of the second 500 mb trough and associated sea-level cyclogenesis were well forecast in IOP 1. NORAPS precipitation forecasts for IOP 1 were remarkably good. The NORAPS model forecast rapid deepening for the explosively deepening cyclone of IOP 9. However, both the NORAPS analyses and forecasts represented the two cyclones observed in IOP 9 as one cyclone. This results from the sparsity of observations in the western North Atlantic Ocean. While rapid deepening was forecast for the explosively deepening cyclone of IOP 9, by 48 h the forecast pressure was 16 mb higher than analyzed.

The next step analyzing in these GALE cases is to quantify the synoptic inferences of this thesis. The diagnostic evaluation of the key terms in the Pettersen development equation and quasi-geostrophic omega equation would reveal the relative importance of upper and lower tropospheric processes in these cyclogenesis cases. The GALE aircraft dropsonde and CLASS data should be integrated into a supplemental data base for re-analysis and re-forecast by the NORAPS model. These new NORAPS analysis and forecast fields then could be compared with the operational NORAPS data. Such a comparison would reveal improvements in NORAPS analyses and forecast to be derived by increasing data resolution. These types of studies, made possible by GALE data, will greatly improve our understanding of maritime cyclogenesis.

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